UNIVERSITY OF ALBERTA

SEDIMENTOLOGY AND STRATIGRAPHY OF THE LOWER CRETACEOUS BLUESKY FORMATION, AITKEN CREEK FIELD, BRITISH COLUMBIA

By

ROBERT HENRY STEPHEN ALWAY ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science.

Deparment of Geology

Edmonton, Alberta

Spring, 1995

ISBN 0-612-01575-0

UNIVERSITY OF ALBERTA

RELEASE FORM

NAME OF AUTHOR: ROBERT HENRY STEPHEN ALWAY

TITLE OF THESIS: SEDIMENTOLOGY AND STRATIGRAPHY OF THE LOWER CRETACEOUS BLUESKY FORMATION, AITKEN CREEK FIELD, BRITISH COLUMBIA.

DEGREE: MASTER OF SCIENCE

YEAR THIS DEGREE GRANTED: 1995

R. Alway

Robert H.S. Alway

2024 - 38 Street, S.E.
Calgary, Alberta.
T2B 0Z6

Date: 94/12/19

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Sedimentology and Stratigraphy of the Lower Cretaceous Bluesky Formation, Aitken Creek Field, British Columbia" submitted by Robert Henry Stephen Alway in partial fulfillment of the requirements for the degree of Master of Science in Geology.

Dr. T. F. Moslow

Dr. C. R. Stelck

Dr. N.W. Rutter

Dr. E.R. Kanasewich

Date: Dec. 19/94

Dedicated to my Undergraduate Professors at the University of Alberta, who taught me how to think.

To D. Scheifner and F. A. Montandon who showed me some things are worth thinking about.

And to my dear parents, Bob and Carolyn Alway, who's sacrifices have made everything possible.

ABSTRACT

A detailed sedimentologic description of 34 cores, core to well log correlation, stratigraphic and structural cross-section correlation of 88 boreholes, palynological analyses of 14 samples (Gething, Bluesky, and Buckinghorse Formations), 14 thin section and 6 scanning electron microscopy analyses were performed to determine the origin of sedimentary facies, sequence stratigraphy, and reservoir characterization of the Bluesky Formation in the Aitken Creek Field. Reservoir facies observed in core from the Aitken Creek Field are interpreted as fluvial and estuarine valley-fill sediments, from the Lower Cretaceous Bluesky Formation, deposited during an early Albian relative sea level still-stand and rise. Depositional sequences comprise a diverse assemblage of facies that can be grouped into lowstand and transgressive systems tracts. River incision is probably a function of eustasy and tectonics, both of which were controlling forces. Incising rivers tend towards topographic minimums, which are accentuated by basement-involved tectonism involving the Hay River Fault zone. The lowstand systems tract comprises a discontinuous unit of relatively thin fluvial conglomerate in the thalweg of the incised valley. The transgressive systems tract comprises the majority of the valley fill, consisting of facies that were deposited in associated estuarine channel, estuarine bay, tidal channel, and outer estuarine environments.

Lowstand fluvial conglomerates form a texturally, relatively homogeneous reservoir. The highly variable transgressive estuarine sandstone facies form a texturally heterogeneous reservoir with anisotropic properties inherited from their primary depositional environment. The primary oil and natural gas reservoir facies is associated with lowstand fluvial conglomerates, displaying the highest porosity and permeability values, due to an early quartz overgrowth cementation phase. Permeability barriers are channel lags, lateral accretion surfaces and lateral facies transitions, the latter applying specifically to estuarine channel and point bar facies, subtidal bay facies, and transgressive shoreface facies. The primary vertical hydrocarbon seal is open marine shales of the Buckinghorse Formation. Lateral hydrocarbon seals are Gething lower delta plain facies, facies transitions from reservoir sandstones and conglomerates to non-reservoir

shales within estuarine and shoreface facies, and structural offset of the various reservoir facies with Buckinghorse Formation open marine shales.

This study establishes a sequence stratigraphic framework and depositional origin for hydrocarbon bearing facies of the Bluesky Formation in the Aitken Creek Field.

ACKNOWLEDGMENTS

As with any research endeavour of this type, completion would not be possible without the financial, technical and moral support of many individuals and institutions.

Financial support for this research was provided by Unocal Canada Limited, Canadian Hunter Exploration Limited, and Union Pacific Resources International. Additional support was provided by an A.A.P.G. grant-in-aid (1992) and Gustavus E. Archie International grant-in-aid (1993), Burn's Memorial Fund Scholarship, and Graduate Teaching Assistantships from the University of Alberta to R.H.S.A.. John MacCrae of the British Columbia Ministry of Energy, Mines and Petroleum Resources and Francois Montandon of Mobil Oil Canada are gratefully acknowledged for in-kind financial support of this project.

I wish to thank Dr. C.R. Stelck (University of Alberta), James Keay, Sydney MacLeod (Unocal Canada Limited), Dave Smith (Canadian Hunter Exploration Limited) and R.W. Evoy for their insights and stimulating discussions on the Cretaceous of northeastern British Columbia. Dave Smith (Canadian Hunter Exploration Limited), Sydney MacLeod and Peter Nanadov (Unocal Canada Liminted) are additionally thanked for their valuable time and assistance in obtaining core analysis and reservoir pressure data, and confidential cores for description in Canadian Hunter Exploration Limited's Calgary, Alberta lab facilities. Palynologic analyses were performed by Dr. Jan Ford, Ford Biostratigraphic Services. Mobil Oil Canada and Lorna Germain are gratefully acknowledge for drafting figures and cross-sections. R.A. Whitworth of Mobil Oil Canada is thanked for granting myself the extra resources and time to complete this thesis. Ichnofossil interpretation was greatly assisted by Dr. S. George Pemberton, Dr. James MacEachern, and Dr. Mike Ranger. The staff of the Charlie Lake Core Storage Facility are thanked for their assistance during my stay in Fort St. John, British Columbia.

Secondly, I am indebted to my mentor Dr. Thomas F. Moslow, even though he still remains a loyal "Bills" and "Blue Devil" fan, for accepting me as one of his graduate students, supervision and editorial comments during each stage of the research. I would like to thank my friends Todd Shenner, Scott Gardner, and Kathy Hamilton for their moral support and encouragement to finish this project, and my buddy Kelly Arnold for the weekly Thursday night "Ratt " ritual . Finally, my parents, Bob and Carolyn Alway, are thanked for their encouragement, the free rent during my summer work terms in Calgary, all of those out of the way trips to Edmonton, "low" interest loans, and the numerous care packages when they were so desperately needed at the end of the semesters.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

TABLE OF CONTENTS (cont.)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (cont.)

LIST OF PLATES

1.0.0. INTRODUCTION

The application of sequence stratigraphic principles has shed new insight into the interpretation of siliciclastic sequences and has reinforced the importance of sea level fluctuations in the formation of incised valleys. Incised valleys form by fluvial erosion of the substrate, sediment by-pass through the eroded valleys, and deposition of sediment at the lowstand shoreline in response to a relative fall in sea level (Van Wagoner *et al.*, 1990). Sediments infill the incised valleys during a relative rise in sea level, generally during the late lowstand and transgressive systems tracts. This is expressed as a basinward shift in facies where non-marine and shallow marine facies, deposited above a sequence boundary, overlie deeper water facies (Van Wagoner *et al.*, 1990).

The stratigraphic and sedimentologic implications of incised valleys within the rock record suggest that they may contain important reservoir facies and represent a new hydrocarbon play concept (Weimer, 1984; Van Wagoner *et al.*, 1990; Blakeney-DeJarnett and Krystinik, 1992; Allen and Posamentier, 1993). Within the subsurface of the Western Canada Sedimentary Basin, incised valleys have been documented in the Cretaceous McMurray Formation (Ranger and Pemberton, 1992), Bluesky Formation (Hardy, 1989; Smith, 1993), Glauconitic Member (Rosenthal, 1988; Strobl, 1988; Brownridge and Moslow, 1991), Viking Formation (Boreen and Walker, 1991; Allen and Posamentier, 1991; Pemberton *et al.*, 1992; Pattison and Walker, 1994), and Dunvegan Formation (Bhattacharya, 1988; Bhattacharya and Walker, 1991).

This thesis focuses on the stratigraphy, sedimentology and reservoir facies relationships of the Lower Cretaceous (Early Albian) Bluesky Formation in the Aitken Creek Field, northeastern Britsh Columbia, Canada (Fig. 1). In this study, reservoir facies are interpreted as fluvial and estuarine valley-fill facies deposited during Early Albian still-stand to early relative sea level rise. The depositional sequence comprises a diverse assemblage of facies that can be grouped into lowstand and transgressive systems tracts.

The depositional model developed for the Aitken Creek Field permits increased understanding and improved assessment of the hydrocarbon potential, reservoir predictability, and hydrocarbon production from reservoirs of similar depositional environments within the Western Canada Sedimentary basin.

1.1.0. ECONOMIC SIGNIFICANCE

Cretaceous stratigraphy in western Canada, according to Podruski *et al.* (1988), is probably the richest in hydrocarbons in the world. Unfortunately, most of the resource occurs either as heavy oil or bitumen which has been biodegraded or exposed to fresh-water at the updip edge of the basin (Podruski *et al.*, 1988). Cretaceous strata of northeastern British Columbia account for approximately 3% and 16% of the in-place and recoverable conventional oil and raw gas reserves, respectively (Fig. 2a, b). The Bluesky play is found in stratigraphically and structurally trapped conglomerate and sandstone reservoirs. The first discovery of the Bluesky Formation in northeastern British Columbia occurred in the Montney Field in 1955. As of December 13, 1992, 48 fields containing 2.8 million cubic meters of oil-in-place and 254

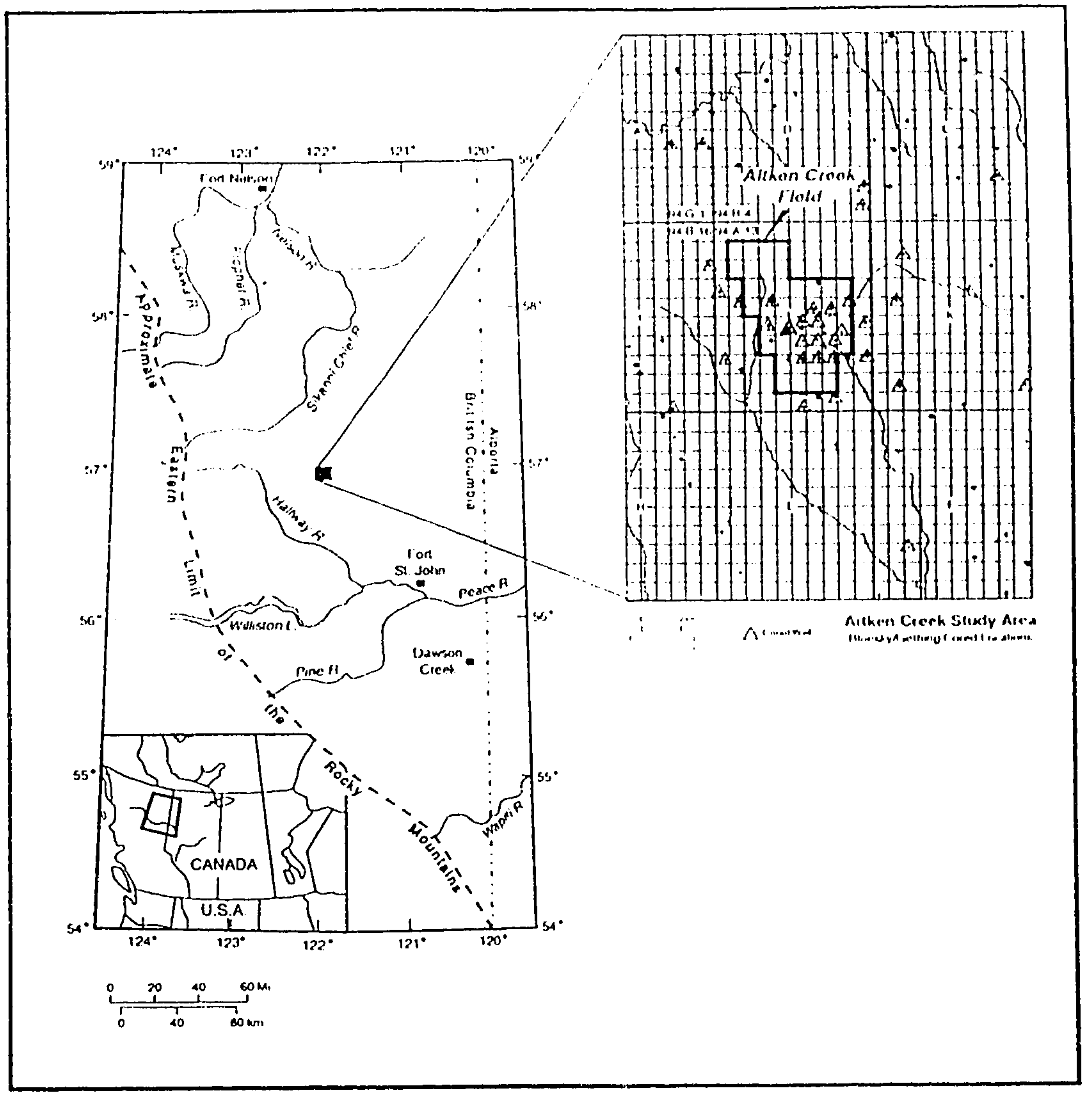


Figure 1. Location map of the Aitken Creek Field, northeastern British Columbia. Bold lines define the boundaries of the Aitken Creek Field (from Alway and Moslow, *in press*).

trillion cubic meters of raw gas-in-place have been discovered within the Bluesky Formation in northeastern British Columbia (British Columbia Ministry of Energy, Mines and Petroleum Resources, 1993). This accounts for 64% of the oil-in-place (Fig. 3a) and 47% of the raw gas-in-place (Fig. 3b) relative to other Cretaceous age hydrocarbon bearing zones in northeastern British Columbia. Podruski *et al*. (1988) suggests that to date only about 40 % of the Upper Mannville Group play, which includes the Bluesky Formation of northeastern British Columbia, has been found in the Western Canada Sedimentary Basin. Further successes will require better understanding of the details of facies changes and lateral correlation and improved depositional models to assist exploration.

1.2.0. PURPOSE OF THE STUDY

This study provides the first documentation of reservoir facies analysis, distribution, geometry and predictability for the Lower Cretaceous Bluesky Formation strata from the Aitken Creek Field. Field scale information can then be extrapolated to regional scale using a sequence stratigraphic framework. Further relationship between marine Bluesky and continental Gething sediments is defined and the geometry of incised valley systems and nature of channel fills within the field is established. All facies types were identified and described. Of prime importance are: a) the interpretation and differentiation of Bluesky marine sediments to determine whether they are associated with channelling events in the underlying Gething deltaic sediments; b) the timing of deposition of shale plugs within Bluesky/Gething channels; and c) the documentation of

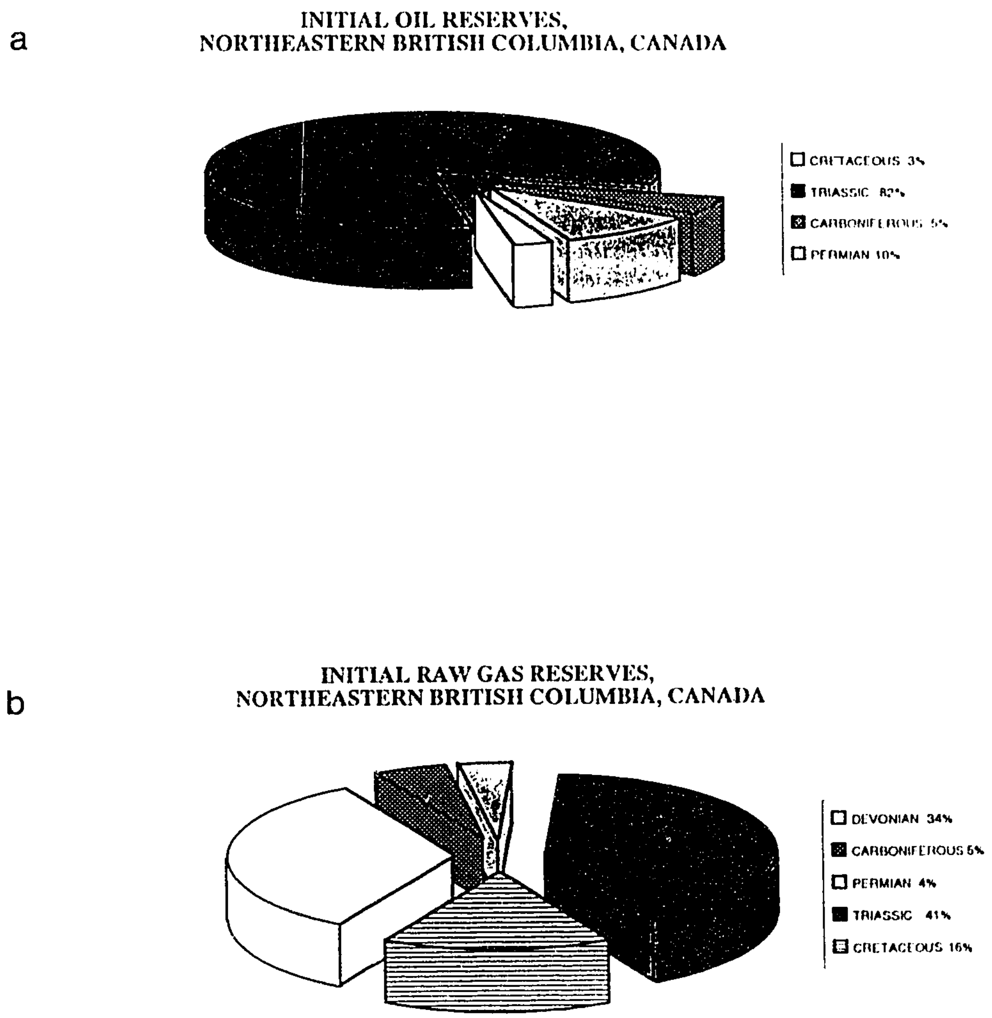


Figure 2. In-place and recoverable oil and raw gas reserves by time period, northeastern British Columbia (Source: British Columbia Ministry of Energy, Mines and Petroleum Resources, 1993).

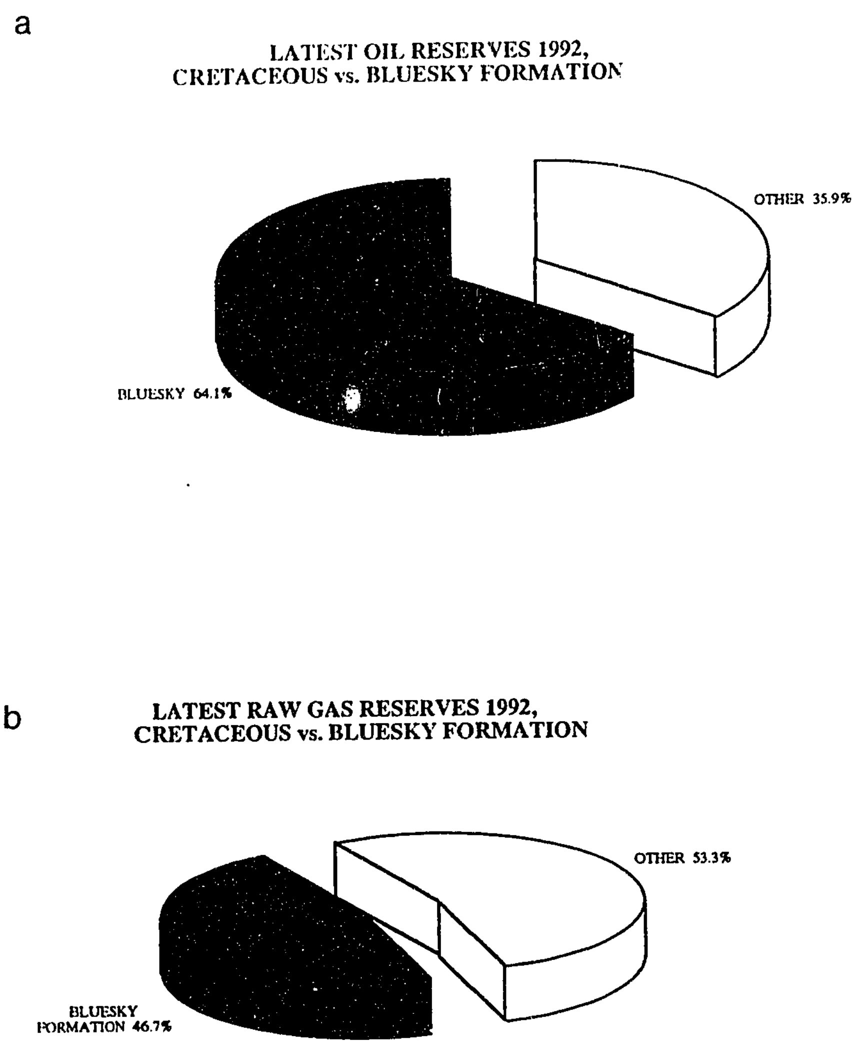


Figure 3. In-place and recoverable oil and raw gas reserves in the Bluesky Formation relative to other producing Cretaceous age formations in British Columbia (Source: British Columbia Ministry of Energy, Mines and Petroleum Resources, 1993).

various styles and patterns of channel facies cross-cutting in the Bluesky equivalent strata.

In order to improve the understanding of reservoir distribution, geometry and predictability, the following objectives were addressed in this study:
1) sedimentological description and identification of subsurface Bluesky sedimentary facies, utilizing a process sedimentological approach. This is achieved by description and division of the core into genetic units from the study of physical and biogenic sedimentary structures, and can be extrapolated to the interpretation of wire-line log signatures. This permits the identification of sequence, parasequence set and parasequence boundaries which will aid in the study of vertical and lateral facies variations of Bluesky sedimentary deposits and vertical stacking patterns of parasequences; 2) identification and description of the nature of contacts at the base of the Bluesky Formation and top of the Gething Formation; 3) environmental interpretation of all facies to allow an accurate assement of their distribution and predicability within the study area, including a determination of the nature of Bluesky sandstone and conglomerate channel fills, the reservoir geometry, architecture, and any heterogeneities in reservoir quality that may exist within the Aitken Creek Field; 4) documentation of sedimentologic controls on reservoir architecture, reservoir quality and heterogeneity; and 5) development of a depositional model of the Bluesky Formation reservoir deposits in the Aitken Creek Field. When completed, the model can be applied regionally as an exploration tool.

1.3.0. STUDY AREA

The study area (Fig. 1) is located in northeastern British Columbia and covers portions of National Topographic System mapsheets 94-A-13, 94-B-16, 94-H-4, and 94-G-1 from a- 001-F/ 94-A-13 to c-100-A/ 94-G-1. This region incorporates the Lower Cretaceous Bluesky and Gething Formations within an area of approximately 644 square kilometers (22.8 km x 27.6 km). The Aitken Creek oilfield is located within the Western Interior Plains, generally refered to as the Peace River Plains, approximately 90 km northwest of Fort St. John, British Columbia.

The Aitken Creek Field is 7.5 km long by 4.0 km wide and contains an average size gas pool and one of the largest oil pools relative to the adjacent lower Cretaceous Fireweed, Buick Creek West and Buick Creek fields. Aitken Creek production is from the Gething 'A' pool, which has produced 2.9 x 10^9 m^3 (102.4 Bcf) of natural gas and 4.7 x 10^5 m^3 (2.96 x 10^6 bbls) of crude oil (British Columbia Ministry of Energy, Mines and Petroleum Resources, 1993). Bluesky production of natural gas is estimated at 1.4 x 10^7 m^3 (0.5 Bcf) (British Columbia Ministry of Energy, Mines and Petroleum Resources, 1993); however, the stratigraphic position of thick channel conglomerate reservoir facies present in Aitken Creek field is problematic when considering the nature, timing and emplacement of thick Bluesky channels within the marginal marine Gething deposits observed in the Western Canada Sedimentary basin .

As of January 01, 1994, 21 wells are drilled in the Aitken Creek Field, at spacings as close as 0.5 km, permitting a high degree of confidence in the

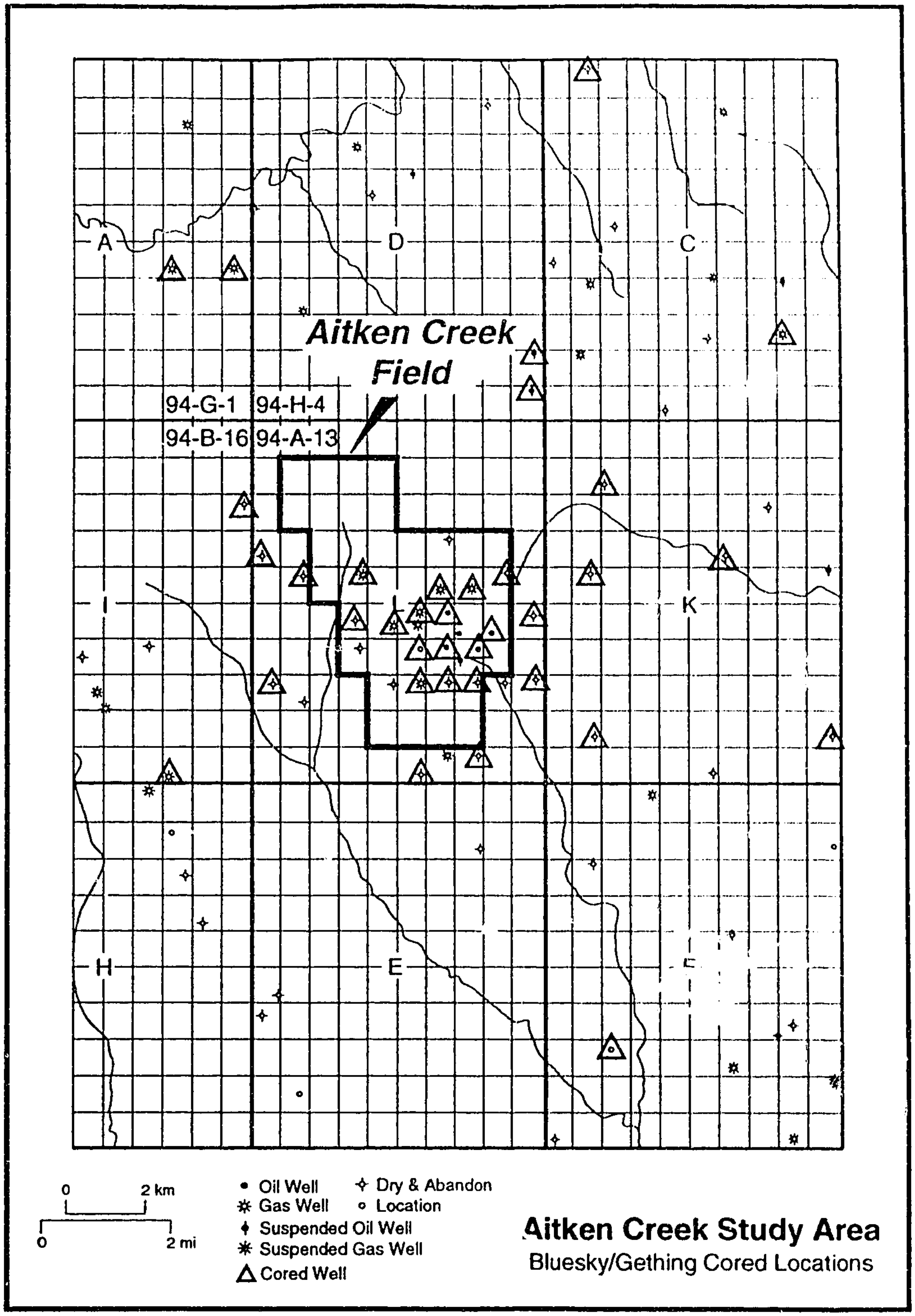


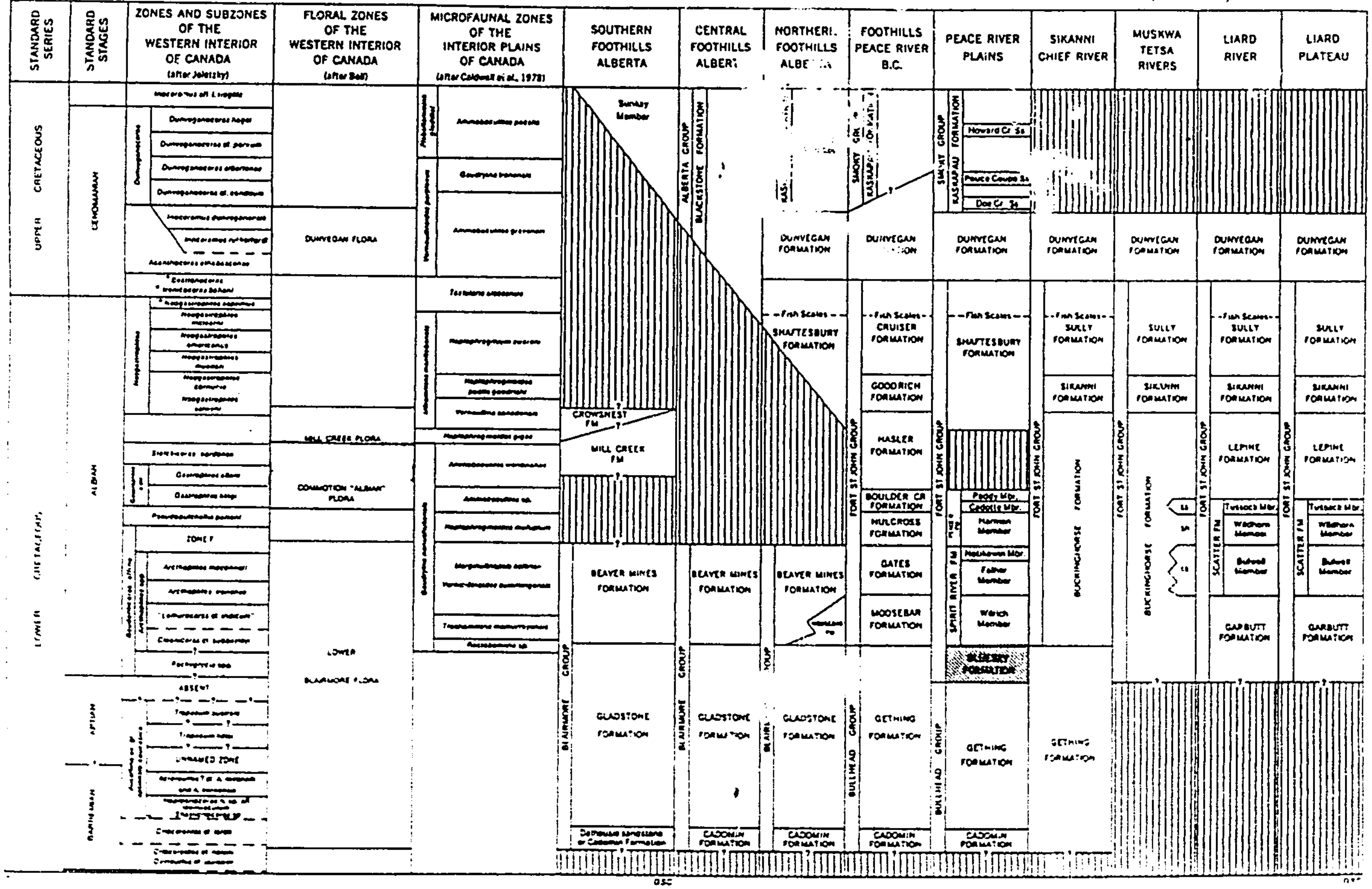
Figure 4. Location map of available Bluesky and Gething Formation conventional drill core data examined in this study.

correlation of facies changes and sequence stratigraphic surfaces or boundaries. Sixty six wells penetrate Lower Cretaceous strata outside of the Aitken Creek Field. The Bluesky Formation was cored in 12 wells within the field, and 17 well outside the field, with the majority of these cores obtained from producing reservoir conglomerates (Fig. 4).

1.4.0. PREVIOUS WORK

Documentation of the Bluesky Formation in the subsurface of northeastern British Columbia is limited. To date, the only studies of chronostratigraphy and depositional proccesses in the Aitken Creek Field vacinity are those of Alway and Moslow (1994, *in press*). The bases for chronologic and regional correlation of Bluesky facies are paleontological and biostratigraphic studies. The earliest paleontologic reports on Lower Cretaceous fossils were made by Whiteaves (1885, 1893). The distribution, composition, and zonation of the Lower Cretaceous fauna were described by McLearn (1929, 1931, 1932, 1933, 1944). Bell (1956) described flora zones within the Western Interior of Canada. Caldwell *et al.*, (1978) presented a summary of the number of earlier studies on microfossil and megafossil zonation. Jeletzky (1964, 1968, 1971) discussed marine marcrofossil zonation, distribution and composition within the Cretaceous of western and Arctic Canada. Stott (1982) provided a summary correlation chart with paleontologic and biostratigraphic information for the lower C[illegible] Fort St. John Group and Upper Cretaceous Dunvegan Formati[illegible] ills and plains of Alberta, British Columbia, District of Mackenzie [illegible] erritiory (Table 1).

Table 1. Summary correlation chart of northeastern British Columbia (Modified from Stott, 1982).



Badgley (1952) produced the first comprehensive study of the Lower Cretaceous series with notes on the subsurface stratigraphy and oil and gas geology in Central Alberta. The Bluesky Formation in the Peace River Arch area was correlated with, and suggested as equivalent to the Wabiskaw and Islay Members of the Clearwater Formation and the *Metacypris angularis* zone in Central Alberta. The Bluesky Formation is commonly difficult to distinguish in well samples where the *Metacypris angularis* zone is missing.

The Alberta Study Group (1954) adopted the term " Bluesky Formation", for a marine offshore sand in the Peace River area. The Bluesky Formation is defined in Shell B.A. Bluesky No. 1 at 04-29-081-01 W6M between the depths of 2736' to 2810', lying between the Bullhead Group and Wilrich shales. A brief summary of the Bluesky Formation history, lithologic characteristics, thickness and distribution, relationship to other stratigraphic units and reference list is present in Stelck (1990). Workman (1959) attemped to correlate Mannville Group stratigraphy with the Blairmore Group and showed Bluesky sandstones to be equivalent to the Glauconite sand in southern Alberta (Table 1).

Glaister (1959) performed a regional study of lower Cretaceous stratigraphy of southern Alberta and northern Montana to produce a general subsurface stratigraphy of southern Alberta. This study integrated previously published outcrop and subsurface data from Mallock (1911), Leach (1912), Stewart (1919), Evans (1929), MacKay (1931), Hume (1932), Beach (1943), Irish (1951) and Clow and Crockford (1951). The Bluesky Formation in the Peace River region was shown to be correlative with the Calcareous member in

Central Alberta and the Glauconite sandstone and Islay member of the Mannville Group in East-Central Alberta. Glaister (1959) placed the Bluesky between the Lower and Upper Blairmore Group and further stated that the Bluesky Formation is related to marine Glauconite sediments representing offshore bar deposits formed during transgression.

Pugh (1960) correlated the Bluesky from the subsurface of Alberta to British Columbia using drilling samples, core and well logs. His correlations were then based on the similarities of lithology and electric-log characteristics. Pugh (1960) assigned the Bluesky in British Columbia to beds, overlying the Gething Formation, which are similar in lithology and electric-log character to those in the Alberta subsurface. In the Peace River area, no contact is observed between Bluesky and Gething beds. To the northwest the Bluesky consists of silty chert pebbles and granules, and beds of rounded and polished pebbles that lie directly on the Gething surface and are interpreted to be erosional (Pugh, 1960). The upper contact between the Bluesky and Wilrich Formations represents a fairly sharp change from sandstone to shale.

Stott (1963, 1968, 1973, 1975, 1982), White (1983), Legun (1984), and Kilby (1984) have published numerous papers and memoirs detailing the distribution of Lower Cretaceous strata in the Rocky Mountain Foothills of Alberta and British Columbia. All restrict the Bluesky to the Peace River plains region of Alberta and British Columbia. North of the British Columbia Peace River Plains region, the Bluesky Formation thins irregularly and eventually disappears. At this point, the Gething Formation is directly overlain by Wilrich shales and equivalents of the Buckinghorse and Moosebar Formations. Pugh

(1960) proposed a disconformable relationship to the north of the Peace River plains where carbonaceous mudstones change abruptly to marine shales.

Duff and Gilchrist (1981) suggest that the basal contact of the Bluesky Formation in the Peace River Coalfield, northeastern British Columbia is abrupt and , while disconformable, no evidence to support a regional unconformity was found. The contact is overlain by 0.25 to 0.5 m thick unit of chert pebble conglomerate, which had been previously correlated to the Bluesky Formtion in the subsurface of the Peace River Plains (Stott, 1968). Duff and Gilchrist (1981) interpret the Chamberlain Member of the Upper Gething Formation to be correlative to the Bluesky Formation of the Plains. They note that this designation would correspond with the suggestion that the Bluesky Formation in the Plains is equvalent to the Gething Formation, not the lower Moosebar Formation (Stott, 1968). This designation has subsequently been questioned by later researchers.

Legun (1987) provided the stratigraphic framework for interpreting the Gething Formation in the southern portion of the coalfields between the Sukunka River and Kinuseo Creek. He suggests that the entire Bullmoose and Chamberlain interval of Gibson (1992) appears to be equivalent to the Bluesky Formation in the Peace River Plains of northeastern British Columbia. As observed by Oppelt (1986), a thin lag of chert-pebble conglomerate, glauconitic sandstone and pebbly mudstone occurs at the top of both the Gaylard and Chamberlain Members of the Gething Formation. These two lags reflect two separate transgressive events that occured within the Moosebar sea (Legun, 1987). The recognition of the glaucontic marker facies, the delineation of the Bullmoose marine tongue in the middle of the Gething Formation and the extension and use of the term Bluesky Formation for these marine strata, have created a nomenclatural and stratigraphic problem (Gibson, 1992).

Gibson (1992) summarized the work of Jeletzky (1971) and Stott (1973; 1982) in a comprehensive report on the stratigraphy of the Lower Cretaceous Gething Formation in northeastern British Columbia and northwestern Alberta, and proposed a new stratigraphic division of the Gething Formation into three members: the basal Gaylard Member, middle Bullmoose Member, and upper Chamberlain Member. The Bluesky Formation is conformable with, and positioned at the top of, the Gaylard Member and is conformably overlain by the Bullmoose Member or Moosebar Formation. This contradicts the work by O'Connell (1988), Oppelt (1988, 1989) and Alway and Moslow (*in press*) who suggest a disconformable relationship exists between the Gaylard Member and Bluesky Formation in northeastern British Columbia. Gibson (1992) reports that the Bullmoose Member north, northwest, east and southeast of the Burnt and Sukunka rivers area thickens at the expense of the overlying Chamberlain Member, and argues that the Bullmoose Member of the Bullhead Group becomes part of, or a facies of the Moosebar Formation of the Fort St. John Group. This relationship can alternatively be explained by a conformable stacking relationship of transgressive deposits containing micro- and macrofossils close in age, and containing no breaks in geologic time. Therefore, this relationship may not permit the stratigraphic distinction between the Bullmoose Member and Moosebar Formation in basinal areas.

Clark (1978) studied the Peace River Plains and suggested that Bluesky sediments record the earliest Cretaceous marine sedimentation within the area. Within this package of marine sediments, Clark (1978) identified two to three sedimentary cycles reflecting minor regressive phases in an overall transgression of the Boreal sea, and suggested that pre-Bluesky topography, combined with wave and current activity of the Boreal Sea, controlled the distribution, deposition and accumulation patterns of the Bluesky Formation in the Peace River Plains.

O'Connell (1988) and Oppelt (1988, 1989) reviewed the sedimentology, stratigraphy and ichnology of the Bluesky Formation in northeastern British Columbia and the Peace River Arch of Alberta and British Columbia, respectively. Oppelt (1989) observed that the Bluesky/ Gething contact is erosional and displays passive infilling of burrowing systems with sediment. The preservation of an omission suite suggests that minimal scouring and reworking of the underlying sediments occured during transgression and emplacement of the overlying trangressive lag (Pemberton *et al.*, 1992). The succession is interpreted to reflect basinward shoreface progradation until relative sea level rise inundates and submerges the shoreline; the associated ravinement strips off the upper shoreface and coastal plain facies. Periodic cessation in trangression, and associated still-stand conditions, allow the development of erosional discontinuities and permit the development of the *Glossifungites* ichnofacies (Pemberton *et al.*, 1992).

Pemberton and Ranger (1991) perfomed multivariate analysis of ichnological associations in the subsurface Bluesky Formation of northwestern Alberta.

Their purpose was to test the use of ichnological associations as keys to paleoenvironmental interpretations in a number of subsurface sedimentologic studies (Pemberton and Ranger, 1991). In these studies, ichnology is used in a quantifiable manner as part of a facies description, yet there appears to be no published studies in which ichnofossils associations in core have been examined using quantified techniques. The above study documented the vertical development and lateral persistence of paleoenvironments. The interpretation is based on statistical treatment of occurence, diversity and association of ichnotaxa.

Hardy (1989) studied the Lower Cretaceous Bluesky Formation in West Central Alberta and noted the presence of anomalously thick Bluesky sediments in the Edson and Pine Creek Fields. These were interpreted to be deposited as an unconformity-bound, estuarine, valley-fill sequence with the top of the Bluesky Formation a transgressive erosional surface accompanied by a sandstone lag.

O'Connell *et al.* (1990) reviewed the depositional facies and facies sequences in the Gething and Bluesky Formations of the Peace River Arch area. Facies variations were interpreted in terms of relative regional sea level rise and local tectonic influence due to reactivation of Peace River Arch. The Bluesky Formation records a period of still-stand with sediments interpreted as mainly storm-dominated shelf sandstones plus local shoreface developments. The upper Bluesky surface is erosional with an associated transgressive marine lag deposit which is overlain by Moosebar-Wilrich marine shales. Subsidence of the Peace River Arch during Bluesky Formation deposition may have resulted in localization and preservation of shoreline deposits in this region.

Leckie and Smith (1992) reviewed the regional setting, evolution and depositional cycles of the Western Canada Foreland Basin. They show that the Bluesky Formation and equivalents were deposited as retrogradational shoreline, estuarine, and shallow shelf deposits. Relative sea-level fluctuations during the depositon of this unit during this time produced incised valley's, estuarine-fill sequences, and local progradational shorelines.

Cant (1994) reviewed the stratigraphy and sedimentology of the Mannville Group concluding that "layer-cake" correlations are inappropriate to the Mannville Group at any scale. He recognized numerous short term relative sea-level fluctuations superimposed upon an overall relative sea-level rise which he attributed to subsidence. Cant (1994) interprets the Bluesky Formation as a series of retrogradational shoreface sequences and estuarine and fluvial valley fills. The top of the transgressive portion of the lower Mannville is considered representative of the Bluesky Formation. The Bluesky Formation underlies, and is completely distinct from the Glauconite Formation, the basal part of the upper progrational portion (Cant, 1994).

Baxter and Smith (1994) studied transgressive sedimentation and shoreface incision of the basal two units within the Early Albian Bluesky Formation, Deep Basin area, Alberta. The two basal units are interpreted to record regressive pulses during the southerly, punctuated transgression of the Moosebar/ Wilrich Sea. The two basal Bluesky units represent back-stepping shoreface parasequences within a transgressive systems tract.

For the most part, these previously mentioned studies focus on areas within Alberta. Other than the stratigraphic studies by Oppelt (1986), Legun (1990) and Gibson (1992), only Alway and Moslow (1994) have presented a chronostratigraphic and depositional model for Early Albian age facies within the Peace River Plains area of Northeastern British Columbia. In order to shed new insight into Early Albian depositional processes, paleogeography, and stratigraphy, a sequence stratigraphic and process sedimentologic approach is employed within the Aitken Creek Field with the results presented in the following chapters.

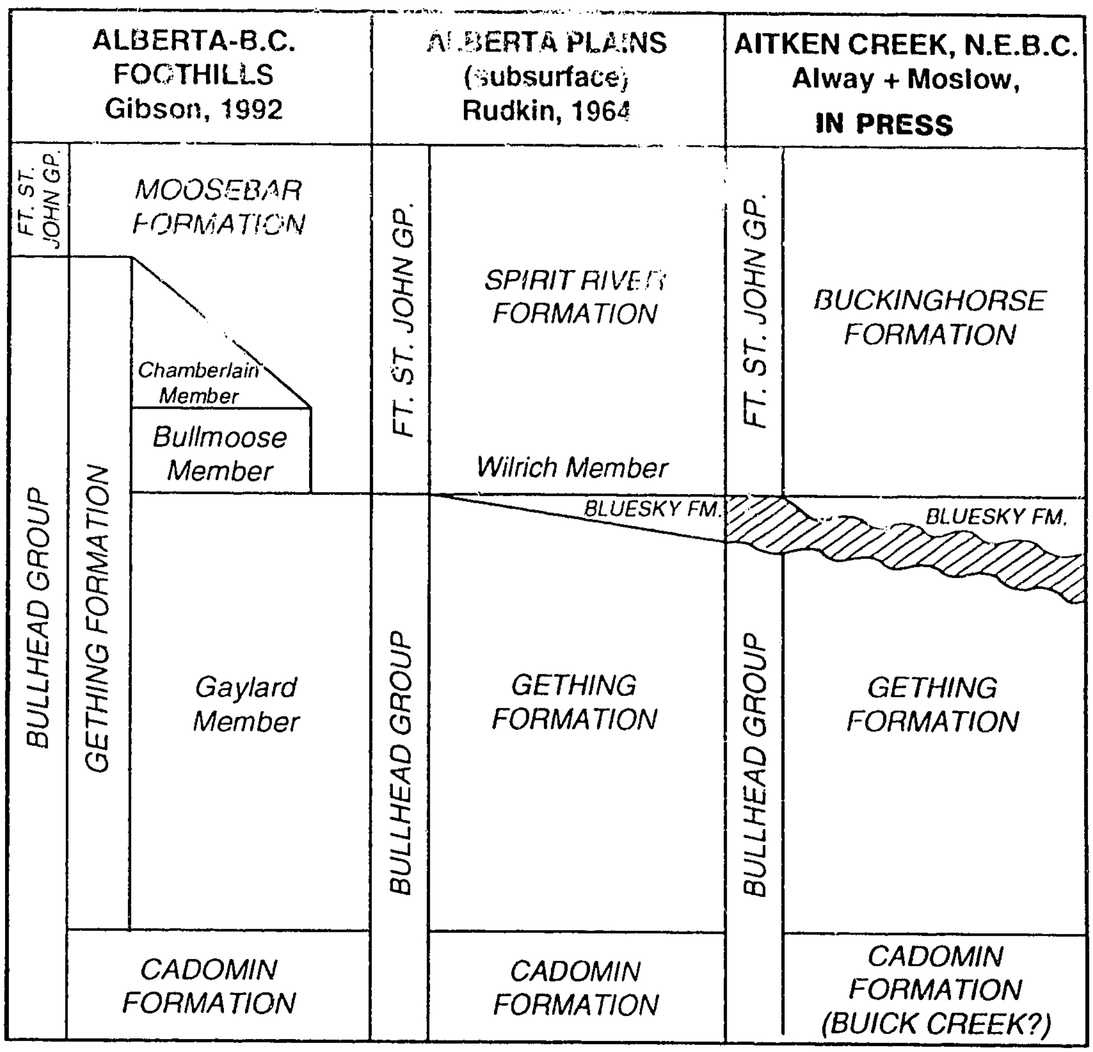
1.4.1. STRATIGRAPHY - BLUESKY FORMATION

The stratigraphy of northeastern British Columbia is discussed in Stott (1963;1973; 1982; 1984), Smith *et al* (1984), and Gibson (1992). Early micro- and macrofaunal zonations are disscussed in Jeletzky (1964; 1968; 1971) and Caldwell et al (1978). Microfaunal, megafaunal, microfloral and megafloral biostratigraphic zonations (Stott, 1963; 1973; 1984) are summarized in Stott (1982) (Table 1). Palynological analyses for the Aitken Creek Field were performed and compiled by Dr. Jan Ford (1994), with the results presented in Table 2. Palynological samples were obtained from within the top 3.0 m of the Gething Formation (below the Bluesky-Gething contact); the abandoned estuarine channel plugs within the Bluesky Formation; and within the basal Buckinghorse Formation, 0.5 m above the Bluesky-Buckinghorse contact.

Table 2. Palynologic analysis and chronostratigraphic framework, Aitken Creek Field by J. Ford, 1994.

Formation	Age	Palynomorphs Represented and Abundance
Buckinghorse	early Albian	*Oligosphaeridium ? diastema* (C) *Chlamydophorella nyei* (C) *C. largissima* (R) *Palaeoperidinium cretaceum* (VR) *Spiniferites ramosus* (VR) *Florentinia* sp (VR) cf. *Hexagonifera* sp (R) *Apteodinium* cf. *reticulatum* (VR) *Cribroperidinium* sp (VR) cf. *Meiouroganyaulax* sp. (VR) cf. *Spinidinium* sp. (R) ? *Acanthaulax* sp. (VR) Dinoflagellates undiff. (R) Bisaccate pollen (C) Spores undiff. (C) *Cerebropollenites mesozoicus* (C) *Lycopodiumsporites* sp. (VR) *Pterospermopsis* sp. (VR).
Bluesky	early Albian	Ceratioid cyst (VR) *Subtilisphaera* cf. *terrula* (VR) ? *Spinidinium* sp. (VR) Bisaccate pollen (R) ? *Cerebropollenites* sp. (VR) *Trilobosporites* sp. (VR) *Trilobosporites apiverrucatus* (VR) Spores undiff (R) *Alisporites grandis* (VR)
Gething	late Aptian-early Albian	? Ceratioid cyst (VR) ? Dinoflagellates (VR) *Alisporites grandis* (VR) *Cicatricosisporites* sp. (R) *Pilosisporites trichopapillosus* (VR) *Contignisporites* sp (VR) ? *Cribroperidinium* sp. (VR) Bisaccate pollen (VR) Spores undiff. (VR-C) *Aequitriradites* sp. (VR) cf. *Spinidinium* sp. (VR) *Cerebropollenites* sp. (R)

Table 3. Correlation chart of the Lower Cretaceous in northeastern British Columbia and northwestern Alberta. The Bluesky Formation is the basal lithostratigraphic unit of the Fort St. John Group (from Alway and Moslow, *in press*).



*MODIFIED FROM GIBSON, 1992

The following Lower Cretaceous formations are defined on the criteria set forth by the above researchers and are represented in Table 3. Within the study area the Bluesky Formation (Fort St. John Group) is underlain by the Gething Formation (Bullhead Group) and overlain by the Buckinghorse Formation (Fort St. John Group).

1.4.2. REGIONAL STRATIGRAPHY AND DISTRIBUTION OF THE BLUESKY FORMATION.

The stratigraphy of the Bluesky Formation is sub-divided and discussed under three sections entitled: A) Definition of the Bluesky Formation; B) Distribution and thickness; and C) Relationship to other stratigraphic units.

1.4.3. DEFINITION OF THE BLUESKY FORMATION:

In Alberta, the Bluesky Formation was first defined by the Alberta Study Group (1954) who based their description on Shell B.A. Bluesky No. 1 located at 04-29-081-01W6M. The Bluesky Formation at the type location is present between 834 meters and 856.5 m, with a total thickness of 22.5 m (White, 1982). The unit was described as:

> " sandstone, brown to brownish grey, fine to medium grained,usually glauconitic, containing fair porosity. Chert granules may appear at the top, decreasing in abundance downwardin the section. There may be thin shale interbeds".

Pugh (1960) proposed using Fort St. John well No. 10 as the type location for the Bluesky Formation in the subsurface of Northeastern British Columbia from 903.0 ft to 941.0 ft. Pugh (1960) described the unit as:

> " 24 feet of very fine-grained, glauconitic sandstone with carbonaceous inclusions, 5 feet of glauconitic, sandy shale and 11 feet of porous, fine-grained, glauconitic sandstone".

The Alberta Study Group (1954) included the Bluesky formation in the Fort St. John group citing the classification by Wickenden and Shaw (1943) of the Fort St. John Group to include all predominantly marine strata lying between the Bullhead Group and Dunvegan Formation . However, Kilby (1983), White (1982), and Karst (1981) have debated whether the Bluesky should be placed within the Moosebar or Gething Formations. Usually the Bluesky is placed within the Gething Formation because of its coarse clastic character and ease of recognition on geophysical logs. Oppelt (1988) suggests the Bluesky Formation should be limited to include only marine and marginal marine sediments deposited directly as a result of Early Albian marine transgression. The overlying Chamberlain Formation, located in northeastern British Columbia, is then separated from the Bluesky due to the continental nature of its sediments (Oppelt, 1988).

1.4.4. Distribution and Thickness of the Early Albian Bluesky Formation

The highest subsurface formation comprising the Lower Cretaceous Bullhead Group is named the Bluesky Formation for the Peace River area of northeastern British Columbia and northwestern Alberta. The thickness

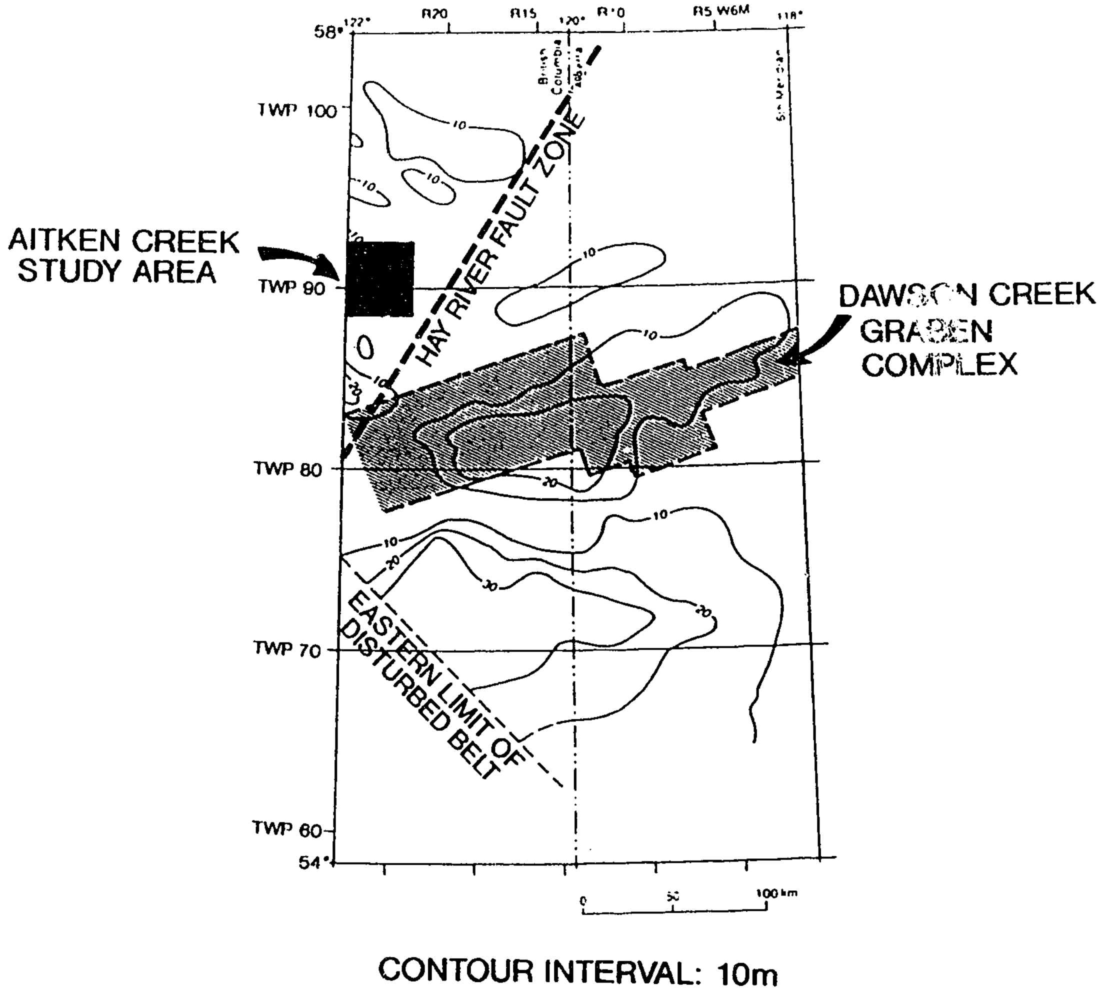


Figure 5. Isopach map of the Bluesky Formation in northeastern British Columbia (modified from O'Connell *et al.*, 1990).

ranges from 0 m to 42 m in the Peace River Plains, thickening irregularly south-southeastwards (Fig. 5). The Bluesky Formation thickens to 46 m in the Pouce Coupe area and pinches out to shale in northwestern Alberta (Stelck, 1990). Thinner sands are encountered north and south of Peace River. The Bluesky Formation is irregularly distributed throughout the Peace River area of British Columbia and Alberta. Two areas of Bluesky non-deposition, which correspond to pre-Cretaceous topographic and structural highs, are located within northeastern British Columbia adjacent to the Alberta-British Columbia border between Townships 95 to 98 and Townships 101-109 (Jackson, 1985). Bluesky non-deposion areas, in central Alberta and northward, correspond to a hinge-line created as a result of Jurassic Cordilleran tectonic activity separating the foredeep trough along the foothills and northwestern Alberta and salt dissolution areas of northeastern Alberta.

Between Sukunka and Wapiti Lake area, the Bluesky Formation is overlain by the coal bearing Chamberlain Formation which in turn is overlain by the Moosebar Formation. A fairly rapid transsgression of the Boreal Sea is suggested by Stott (1982). Taylor and Walker (1984) described an abrupt change from Gething continental deposits to Moosebar marine shales. In the Peace River area, the Bluesky Formation consists of mainly coarsening-up, isolated "sand bars", with thicknesses of 30 m or more (Oppelt, 1988). Where "sand bars" are absent, the Bluesky is represented by a thin conglomeratic veneer.

1.4.5. RELATIONSHIP TO OTHER STRATIGRAPHIC UNITS

The base of the Bluesky is defined by a thin polymictic basal conglomerate with a sharp contact, often bioturbated at the base, conformably and disconformably overlying sandstones, shales and coals of the Gething Formation and resting unconformably on the subcropping Triassic and Mississippian strata north and east of the Peace River town site (Stelck, 1990). The contact represents a significant change in sedimentation style from continental to transgressive marine deposits.

In the northern part of the region a restricted basin already existed, causing only a slight break in sedimentation to occur, with the Bluesky/ Gething contact illustrating a sedimentary succession which is almost gradational (Stott, 1973). The Gething-Buckinghorse contact appears conformable and displays no break in sedimentation. Northwest of the Peace River region, the Bluesky Formation (Fig. 6) consists of a chert granule and pebble lag deposit resting directly on top of the Gething surface sugessting that the surface may have been eroded (Pugh, 1960). Cant (1989) interpreted the surface as a *ravinement surface* - a surface cut during a marine transgression as the shoreface passed over Gething delta plain and continental sedimentary deposits. South of Peace River, marine muds were directly deposited over Gething alluvial sediments (Stott, 1973). This suggests that Gething sediments were being eroded there or the area was temporarily the site of non-deposition immediately prior to the advance of the Boreal Sea (Stott, 1973). In this region, the Gething-Moosebar contact is disconformable. The upper contact of the Gething-Moosebar Formations is exposed at Moosebar, Aylard, and Gething Creeks (Stott, 1973). The boundary at these locations is distinct and probably slightly disconformable throughout the region (Stott, 1973). The Bluesky Formation appears to have a similar northward extension as the underlying Gething Formation (Pugh, 1960).

Over large areas of central and southern Alberta the Bluesky Formation is underlain by the Ostracod Member of the Mannville Group (Law, 1954). The Bluesky Formation is conformably overlain by the Wilrich Member of the Spirit River Formation in the Peace River region and southeastward and elsewhere in Alberta by continental to marine facies of the Blairmore Group (Law, 1954). This upper contact represents a sharp and fairly abrupt change from sandstone to shale. Stelck (1990) suggested that the Bluesky Formation is in effect the homotaxial shallow bar facies of the Wilrich marine transgression. The Bluesky Formation (Table 1), in northeastern British Columbia, is considered laterally equivalent to the Bluesky Formation in the Peace River region, Alberta, the Ostracod and Glauconitic Formations of the Mannville Group in central and southern Alberta (Strobl, 1988; Jervey, 1992; Smith, 1993), the Cummings Formation of the Mannville Group in East-Central Alberta, and the Wabiskaw Member of the Clearwater Formation in the lower Athabasca River area of Northeastern Alberta (Stelck, 1990).

1.4.6. LOWER CRETACEOUS UNCONFORMITY, AITKEN CREEK STUDY AREA

Lower Cretaceous stratigraphy may be interpreted in terms of Cordilleran tectonics, which in effect, initiated sea-level fluctuations in the foreland basin.

Cant and Stockmal (1989) suggest that accretion times of various terranes were coincident with the deposition of equivalent formations in the foreland basin. Early Cretaceous truncation of pre-exisitng formations did not completely remove the underlying Triassic and Jurassic sediments at Aitken Creek. The pre-Cretaceous erosion surface is an angular unconformity representing a period of tectonic reorganiztion.

The unconformity is variably expressed throughout the study and its recognition is dependent on the stratigraphic units above and below this surface (Fig. 6). In western areas of the study, sandstones and conglomerates of the Buick Creek Formation overly shales of the Fernie Group. However, in the eastern section of the study, sandstones, siltstone, mudstones and coals of the Gething Formation disconformably overly shales of the Fernie group, making the distinction between the two units difficult. The gamma ray signature is slightly less radioactive for the Gething Formation and generally there is a well defined smooth or tight linear response on the sonic log. Definition of the Gething Formation and Fernie Group has an added difficulty when correlating southward in the study, where the Gething Formation thickens and thins abruptly above features associated with collapse of the Peace River Arch (O'Connell *et al*, 1990) and above normal faults of the Hay River Fault Zone (Stelck, 1975).

1.5.0. METHODS

This study incorporates process sedimentology and the principles of sequence stratigraphy into a study of reservoir facies and architecture, depositional facies and systems tracts of the Aitken Creek Field. Methods to be applied are outlined below.

1. Process sedimentology is applied to study the sedimentary facies of the Bluesky Formation, Aitken Creek Field, northeastern British Columbia. This approach involves the description and division of cored Bluesky zones into genetic units based on the study of physical and biogenic sedimentary structures. This information is then used to identify depositional processes which in turn, provide information for the interpretation of the environment of deposition.

2. Sequence stratigraphic principles are applied to study the Aitken Creek Field, northeastern British Columbia. The depositional sequence, which includes the Bluesky and lower Buckinghorse Formations, will be sub-divided into systems tracts, which are defined by the stacking patterns of parasequence sets and parasequences. Sequences , parasequence sets, and parasequences are defined and identified by the lateral continuity and geometry of the bounding surfaces, physical relationships of the strata, lateral and vertical stacking patterns, and lateral geometry of strata within these units (Van Wagoner *et al*, 1988). The boundaries of these stratal elements form a chronstratigraphic framework for mapping and correlation of Bluesky Formation deposits.

1.5.1. DATA BASE

As of January 01, 1994, the data base includes petrophysical well log responses of 88 boreholes. The study area has the added advantage that the underlying

Lower Cretaceous Buick Creek Member, Dunlevy Formation, and various Triassic and Mississippian Formations are also potential hydrocarbon reservoirs, resulting in full coverage of Bullhead and Fort St. John Group stratigraphic intervals. This coverage permitted a variety of formations to be analyzed in order to document structural reactivation of basement faults associated with the Hay River Fault zone which influenced the course of incising rivers. A disadvantage to the selection of this area is the quality of the data available. The original discovery well for the Aitken Creek oilfield, UNION AITKEN CREEK a-53-L, was completed in early 1959. Most of the wells in the study area have a poor to good quality full suite, or partial suite, of wireline logs of varying vintage.

A list of cored intervals (Gething, Bluesky, and Buckinghorse Formation) (Appendix A), core analysis and production data was supplied by Unocal Canada Limited and Canadian Hunter Exploration Limited, and cross-referenced with well completion records supplied by Digitech Systems. Core coverage is generally restricted to the lower half of the reservoir within the reservoir. Ten wells core the Aitken Creek Field. Two wells provide additional recovered core from the upper half of the field (Fig. 4). An expanded study area was required to provide additional core coverage to study the Bluesky reservoir facies located within the upper half of the Bluesky Formation in the Aitken Creek Field. In total, 34 cored intervals were described in detail for the purposes of identifying sedimentary facies, lateral facies variations, formation contacts and significant sequence stratigraphic surfaces within the Aitken Creek Field. Core to well log response correlation facilitated correlation of sedimentary units between boreholes where there were no cored intervals.

Thin sections from 8 conglomerate and 6 sandstones were studied petrographically. S.E.M. analysis of 6 samples from reservoir and non-reservoir cored intervals facilitated the identification of clays and cements within the pore network of reservoir sediments. Fourteen core samples were selected from seven wells in the Aitken Creek field and surrounding acreage and processed for palynology and kerogen analysis to obtain information regarding the age and environment of deposition. Two of the sections (d-033-L/ 94-A-13 and b-042-L/ 94-A-13) intersect the reservoir unit, the other sections consist entirely of channel-fill, marginal marine and bay-fill sediments. A suite of stratigraphic, structural and facies cross-sections were constructed to determine hydrocarbon trapping mechanisms, lateral facies relationships and geometry of incised valley fills relative to regional Gething Formation deposits. Isopach maps of the identified parasequences within the Bluesky Formation at Aitken Creek were hand contoured and mapped at a scale of 1: 50 000.

1.5.2. Core Descriptions

The procedures practiced in measuring and describing cored sequences are similar to studying a section in outcrop, except that the amount of available section for analysis is restricted, and it is impossible to observe lateral changes in lithology or sediment body geometry. When beginning a sedimentological interpretation of a cored sequence, it is critical to utilize all available information and to make maximum use of the vertical sequences.

The initial procedure followed in core descriptions was to verify the correct orientation of the core pieces and to confirm the length of the core, assessing the degree of core loss. This permits an accurate record of the characteristics pertinent to the interpretation of lithologic sequence:

1. primary (depositional) sediment composition and texture
2. grain texture (size, sorting, roundness, sphericity, maturity, sediment composition and percentage)
3. nature of bedding and facies contacts
4. primary physical sedimentary structures
5. biogenic sedimentary structures
6. secondary (deformational) sedimentary structures
7. macroscopic diagenic features.
8. unit and bed thickness
9. nature and type of porosity present

This descriptive format guarantees that all significant aspects of the core are recorded and consistent with sucessive descriptions. Core information is recorded on core logging sheets at scales of 1:10 or 1:50. This log provides a written summary of the core, and illustrates the vertical distribution, contact relationships, and sedimentary characterisitics of the cored interval. Core descriptions are provided in Appendix A.

1.5.3. Process Sedimentology - Genetic Units

A process sedimentologic approach was applied to the analysis of subsurface Bluesky Formation strata in the Aitken Creek Field. This approach documents the origin of sedimentary deposit by careful observation of details and recognition of genetic units in vertical cored sequences. Genetic units are " lithologic units that display features which originated from processes that were relatively constant, or varied in a uniform manner, throughout the formation of these lithologic units" (Seimers and Tillman, 1981). Several forms of genetic units are recognized, dependent on the dominant process which shaped the deposit. These are sedimentation units, ichnogenic units, soft-sediment deformation units, and diagenic units.

1.5.4. Log Correlations

The gamma ray and acoustic logs were the primary log tracts used for correlation of formation boundaries, lithofacies, and sequence stratigraphic surfaces within the Aitken Creek reservoir and surrounding acreage. These log tracts were chosen because they were run within the majority of the wells penetrating the Aitken Creek reservoir and surrounding acreage, thus, permitting correlation of lateral facies relationships. The gamma ray log measures natural formation radioactivity and therefore can be used to identify lithologies and aid in the correlations of zones (Asquith, 1983). Shale-free sandstones and carbonates contain low concentration of radioactive minerals. As the shale content increases, the readings on the gamma ray log increase concomitant with increasing radioactive mineral content. However, sandstones with low shale content can also produce high gamma ray response if significant radioactive minerals or uranium-rich waters are present . In addition, gamma ray logs can be used to provide information for the estimation of shale volume present within a zone (Asquith, 1983). Acoustic logs measures the velocity of compressional sound wave passing through one foot of formation. The acoustic log can be used to measure both porosity and lithology. Sandstones, limestones and have low interval travel times (high velocities); under-compacted coals and shales have high interval travel times (low velocities) (Readings, 1986). Described cored intervals of the wells were compared with the log tracts to further the accuracy of the lithologies indicated on well logs of cored and non-cored intervals.

1.5.5. SAMPLING AND PHOTOGRAHPY

Representative samples were cut from both reservoir and non-reservoir intervals within the Aitken Creek Field, and from surrounding acreage. Selected intervals were chosen for palynologic analysis and petrographic study of each facies. Photographs of each facies were taken at the Charlie Lake Core Storage Facility to provide a record of the sedimentary structures, biogenic structures, and contacts present , and for later comparison with in different fields adjacent to Aitken Creek.

The analysis of microfossils and the associated organic matter (kerogen) is a convenient, accurate and, in the absence of distinctive macrofauna, sometimes the only way to determining the age and depositional environment of certain rock units. Palynologic analyses for this study were contracted to Ford Biostratigraphic Services in Calgary, Alberta.

2.0.0. GEOLOGIC FRAMEWORK

This chapter provides a geological framework for the Bluesky Formation within Lower Cretaceous stratigraphic section of northeastern British Columbia. Included in this section will be discussions on tectonic setting and controls on sediment distribution, global sea level, basin configuration, regional paleogeographic setting, sediment source and paleoclimate.

2.1.0. TECTONIC SETTING

Evolutionary model for the development and characteristics of a foreland basin illustrate an asymmetric structural depression which deepens towards the bordering thrust and fold belt, which serves as the primary source for basin filling sediment (Fig. 7). The asymmetry of the foreland basin is primarily due to lithospheric flexure, reflecting the distribution of tectonic activity and relative subsidence (Kauffman, 1977; 1982; Jordan, 1981).

The Western Canada Foreland basin can be subdivided into five, northwest-southeast trending, physiogeographic zones based on variation in water depths, sedimentation rates, facies, subsidence rates and stability (Fig. 7) (Kauffman, 1977; McNeil and Caldwell, 1981; Leckie, 1989; Leckie and Smith, 1992). In addition to the actual fold-thrust belt in the west and the stable craton in the east, this includes 3 major zones of sediment accumulation.

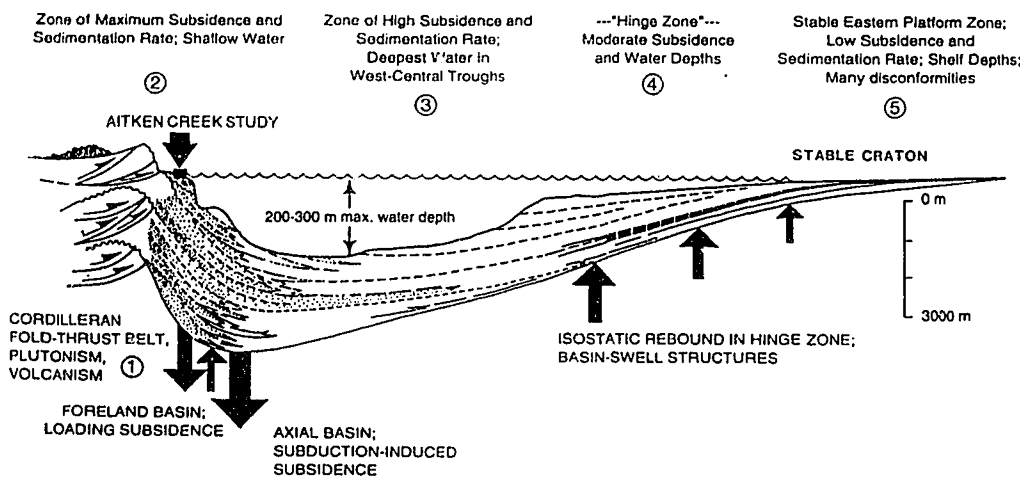


Figure 7. Idealized structural and stratigraphic cross-section across the Western Canada foreland basin at a time of maximum transgression. The positions, directions, and sizes of arrows indicate relative thrusting, subisdence, and uplift. (modified from Kauffman, 1984; Leckie and Smith, 1992).

The trough immediately bordering the thrust and fold belt is a zone of maximum subsidence and relatively high sedimentation rates. Sediments consist of coarse-grained clastics sourced from the tectonically active thrust and fold belt. Shallow marine to coastal plain environments dominate this belt within the foreland basin. The Bluesky Formation at Aitken Creek is interpreted to lie within this zone.

Eastward of this deep trough bordering the thrust and fold belt, is a zone of high subsidence and sedimentation rates, mainly involving deep, quiet water environments. Fine clastics, predominantly thick, dark shales and silty shales, with numerous interbedded sandstone tongues from western sources are deposited during progradation and/ or regressive pulses (Kauffman, 1977; 1982).

A broad hinge zone develops between the foreland basin and a sub-basin in the east produced by salt withdrawl from Paleozoic formations. The subsidence and sedimentation rates observed associated with the hinge zone are moderate to low, with relatively thin, fine-grained carbonate, silty clay and clay units commonly eroded by large and small disconformities (Kauffman, 1977;1982).

2.1.1. Intracratonic Tectonic Elements

The foreland basin is shown to be divided by two large basement structures which originated in the pre-Paleozoic and Paleozoic, but still affected sedimentation in the Cretaceous; these units are the Peace River Arch in northwestern Alberta and northeastern British Columbia and the Sweet Grass

Arch in Southern Alberta (Cant, 1989). These structures moved up and down, possibly in response to thrust loading in the Cordillera, which affected the stratigraphy, facies distribution, and thicknesses of the units overlying them (Cant, 1989). Local reactivation of Paleozoic faults has caused offset of Cretaceous sedimentary units within the foreland basin. During the Lower Cretaceous, four subtle structural features have been shown to influence sedimentation patterns in northeast British Columbia. These four features (Fig. 8) are the the Peace River Arch- Dawson Creek Graben Complex (O'Connell *et al.*, 1990), Liard or Gething trough, Omineca Crystalline belt (Stott, 1973), and the foreland hinge belt located east of the Gething Trough (Stott, 1982; 1984).

The Peace River Arch is a Late Proterozoic cratonic basement uplift feature which formed at a high angle to the passive margin and has existed in three different forms throughout its history: 1). a Late Proterozoic to Early Paleozoic arch; 2). Later Paleozoic to earliest Mesozoic embayment; and 3) a deep basin component of the Mesozoic foreland basin (Cant, 1988; O'Connell *et al.*., 1990). The collapse of the Peace River Arch initiated in Mississippian time (Stott, 1982; Cant, 1988; O'Connell *et al.*, 1990). The depositional trends of Lower Cretaceous Aptian and Albian sediments show the influence of the subsiding nature of the Arch; O'Connell *et al.* (1990) show areas of localized subsidence to have occured in the Peace River region, and the area underlying the Peace River Arch (Fig. 5). This suggests possible arch-related structural control of Cretaceous basin configuration and facies distributions. The Aptian Gething Formation consists of continental to coastal plain sediments that were deposited in a northwest-trending valley, and thin in a northwest direction. The thinning trend is interrupted by the southern axis of the Peace River Arch where

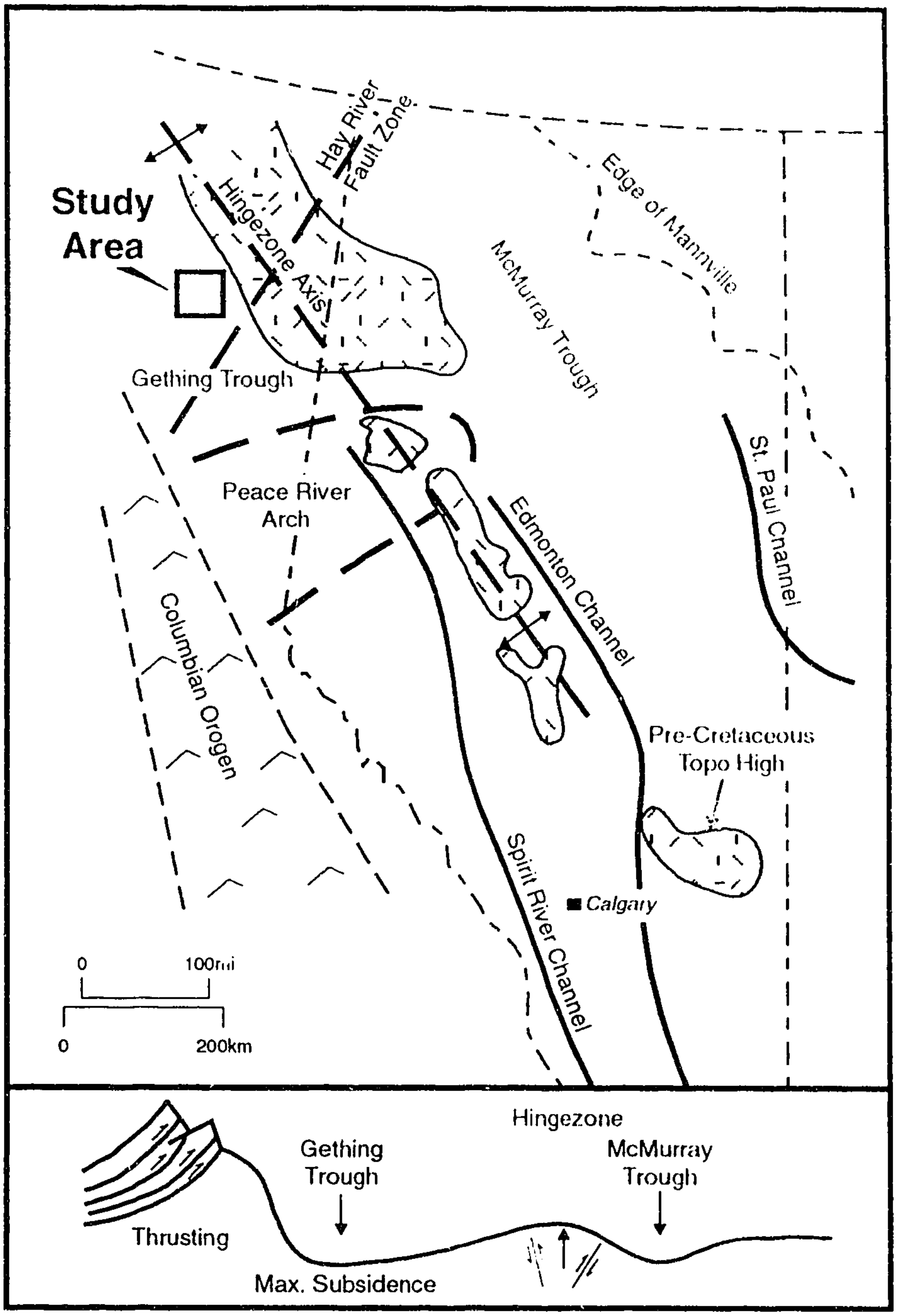


Figure 8. Tectonic elements controlling Cretaceous deposition (modified from Stott, 1982; and Oppelt, 1988).

an abrupt northeast trend of thickening within the Gething Formation occurs parallel to the Dawson Creek Graben Complex (Stott, 1973; Smith *et al.*, 1984; O'Connell, 1990). In northeastern British Columbia, the Bluesky Formation overlies the Gething Formation, and consists of beach, shoreface and shallow marine sediments. The largest of the shallow marine sandbodies, interpreted as inner shelf shoal deposits by O'Connell (1990), is suggested to be deposited within the structural boundaries of the underlying Dawson Creek Graben Complex. This suggests the preferential preservation of the offshore sand units as a result of subsidence of the Dawson Creek Graben Complex. This preferential preservation is observed in the Aitken Creek Field where structure cross-sections and structure contour maps illustrate normal faulting associated with reactivation of pre-existing faults influencing fluvial drainage patterns and the preservation of lowstand fluvial conglomerates.

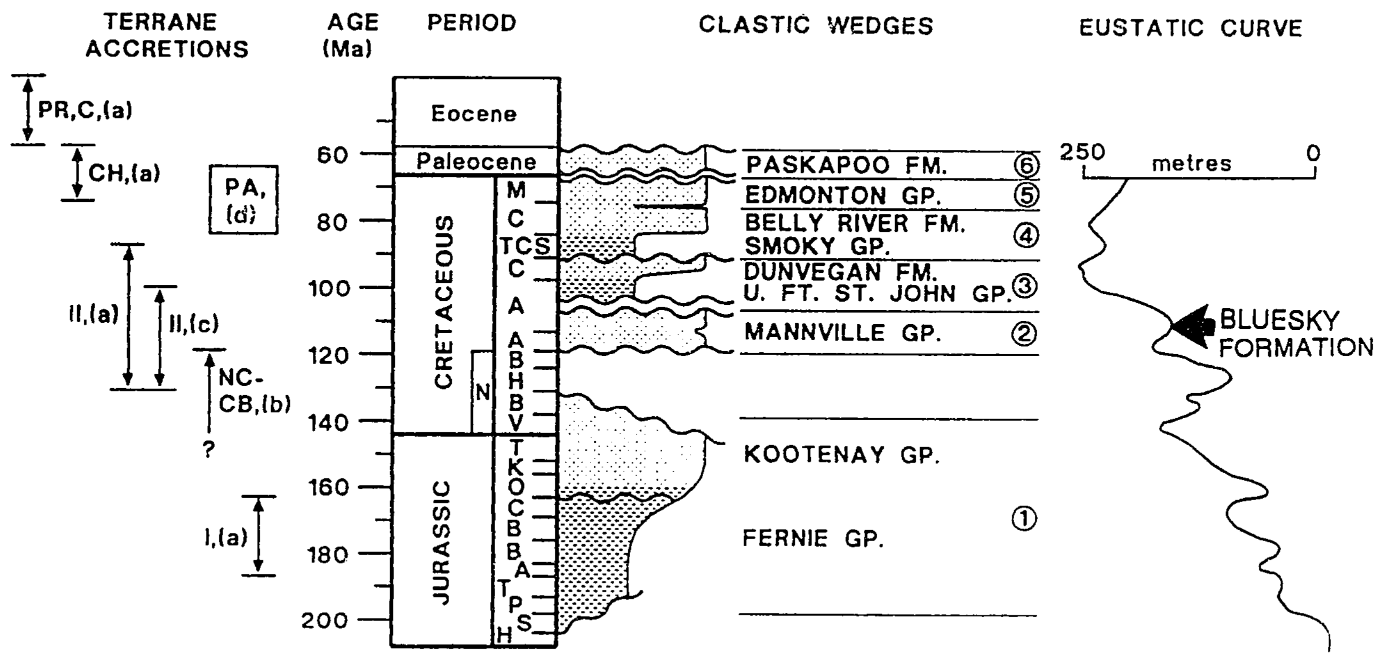
The Gething Trough (Fig. 8) (Stott, 1984; Smith *et al.*, 1984), containing areas which include the Hay River-Keg River Low (Stelck, 1975) is a structural depression lying between the Peace River Arch in the south, foredeep hinge zone in the east, and the Rocky Mountain thrust and fold belt in the west. It is intersected near its northern end by the Hay River Fault zone. Stelck (1975) suggests that the Keg River Low acted as a favoured area for the reception of Lower Cretaceous clastic wedges. Stelck (1975) suggests that due to diastrophic (Aptian) and orogenic tilt to the east, drainage patterns of the Middle Cretaceous reversed direction and flowed eastward to empty into an embayment of the Arctic Ocean. The maximum delta fill in Late Aptian-Early Albian time occured in a geographic region north of the Peace River Arch and south of the Hay River Fault zone. Some basement control is suggested by the major infill of the Gething coal sequences based on isopach maps of O'Connell *et al.* (1990), Cant (1988), Stott (1984) and Leckie *et al.* (1990). The trend of the Hay River Fault zone strongly influenced the underlying Gething fluvial drainage systems which illustrate a southwest-northeasterly trend coincident with the fault zone (D. Smith, pers. comm., 1994). Therefore, the Hay River Fault zone rather than the Dawson Creek Graben Complex, which is located farther south of the Hay River Fault zone, is favoured as the tectonic element responsible for the structural features at Aitken Creek.

2.1.2. RELATIONSHIP OF TECTONICS TO DETAILED STRATIGRAPHY

The general stratigraphy of Cretaceous strata in the Western Canada Sedimentary basin suggests the foreland clastic succession can be divided into five (Leckie and Smith, 1992) or six (Cant and Stockmal, 1989; Stockmal *et al*, 1992) distinct clastic wedges which can be correlated with tectonic loading events. Stockmal *et al.* (1992) emphasizes the separation of the Belly River Formation from the Edmonton Group which results in the sixth cycle within the Western Canada Sedimentary Basin (Fig. 9).

The Late Jurassic Kootenay-Fernie clastic wedge had been bevelled by the pre-Mannville Group erosion. The base of the Bullhead Group marks the Jurassic-Cretaceous contact, although significant amounts of time are missing in this interval (Rosenthal, 1988; Cant and Stockmal, 1989; Cant, 1990). In general, the term Bullhead originally included the Beatie Peaks and Neocomian portion of the lithic greywackes which represented the Lower Bullhead Group (Stelck, pers. comm., 1994). The more quartzose sandstones of the Jurassic were

Figure 9. The six-first order clastic wedges of the Western Canada foreland basin shown as a function of time, with a eustatic sea level curve from Haq *et al.* .(1987), and the times of accretion of allochthonous terranes taken from: Gabrielse and Yorath (1989); Monger *et al.* (in press); and Thorkelson and Smith (1989). Relative position of the Bluesky Formation is indicated to the right. I = Intermontane superterrane; NC-CB = North Cascades and Coastal belt terranes; II = Insular superterrane; CH = Chugach terrane; PR = Pacific Rim terrane; and C = Crescent terrane. Eustatic drops are seen not to correspond in any general way with the stratigraphy, with a possible exception at approximately 125 Ma, where the brief relative lowstand may have enhanced tectonic uplift effects. Shown also is the period of development of the Purcell Anticlinorium (PA), as given by Price (1981) (modified from Stockmal *et al.*, 1992).



TERRANE ACCRETIONS
AGE (Ma)
PERIOD
CLASTIC WEDGES
EUSTATIC CURVE
PR,C,(a)
CH,(a)
PA, (d)
II,(a)
II,(c)
NC-CB,(b)
?
I,(a)
60
80
100
120
140
160
180
200
Eocene
Paleocene
CRETACEOUS
JURASSIC
N
M
C
TCS
C
A
A
B
H
B
V
T
K
O
C
B
B
A
T
P
S
H
PASKAPOO FM.
EDMONTON GP.
BELLY RIVER FM.
SMOKY GP.
DUNVEGAN FM.
U. FT. ST. JOHN GP.
MANNVILLE GP.
KOOTENAY GP.
FERNIE GP.
⑥
⑤
④
③
②
①
250
metres
0
BLUESKY FORMATION

usually called Nikanassin, now known as Minnes Group. So for northeastern British Columbia, the statement as to the base of the Bullhead Group traditionally must include the Montieth, Monach, Beattie Peaks, Cadomin and Gething Formations (Stelck, pers. comm., 1994). However, Stott (1982) subdivided the Bullhead Group into two formations in northeastern British Columbia; the lower Cadomin Formation and the upper Gething Formation (Table 1). Widely dispersed, coarse Cadomin conglomerates have commonly been attributed to major uplift along the Omineca Belt and attendent erosion of thrusted miogeoclinal strata (Cant, 1990).

The gradual decrease in conglomerate thickness and clast size of Upper Gething and Lower Bluesky deposits are interpreted to reflect gradual erosion of the highlands and a progressive decrease in the volume of sediment reaching the basin (Stott, 1973). Rapid subsidence during this time can be accredited to tectonism coincident with accretion of Terrane I approximately 100 million years ago (Chamberlain *et al.*, 1989). Eventually as sedimentation rates were exceeded by basin subsidence, the Boreal Sea began transgressing southeastward along the Gething Trough. As the hinterland became reduced in elevation and the amount of material supplied to the basin diminished, and the rate of subsidence exceeded sedimentation. Transgressive deposits of the upper Bluesky, Moosebar and Buckinghorse Formations reflect a lull in tectonic activity during Early to early Middle Albian time (Stott,1973)

2.2.0. T-R CYCLES, WESTERN CANADA SEDIMENTARY BASIN

Vail *et al.* (1977) suggests eustatic changes in sea level on a global scale may result from a change in the absolute volume of sea water, in the configuration of the ocean floor, or a combination of both. Increasing or decreasing the absolute volume of water required to raise and lower sea level substantially through climatic processes is improbable in the generation of eustatic sea level fluctuations within the Western Interior Seaway during the Lower Cretaceous. Paleoclimate trends during Cretaceous time suggest greenhouse conditions prevail, with warm, equitable climates (Stott, 1973), and no significant continental glaciaticn.

An alternative explanation to glaciation for eustasy is through accelerated plate spreading and the resultant topographic build-up along a positive spreading centre. The volumetric displacement of water associated with increased seafloor topography and apparent subsidence in the foreland basin led to epicontintental flooding of 300 meters or more during Cretaceous time (Kauffman, 1984; Haq *et al.* , 1987). "Subsidence rates" of 10 m/Myr in the Western Canada Sedimentary Basin (Chamberlain *et al.*, 1989) can be attributed to eustasy induced by sea-floor spreading. Any subsidence rates greater and/or occurring at times other than those identified as eustatic sea-level fluctuations, cannot be accredited with eustasy (Chamberlain *et al.*, 1989).

There is considerable disagreement as to whether controls on epicontinental flooding are primarily eustatic or regional tectonic, climatic and sedimentologic phenomena. Kauffman (1973; 1976; 1977; 1984) used high resolution biostratigraphic and geochronologic methods to correlate regional transgressive-regressive cycles. World wide correlation of the peaks of transgression and regression are interpreted as reflecting tectono-eustasy. Weimer (1984) concentrated on the relationship between unconformities, tectonics, and sea level changes within the Cretaceous Western Interior Seaway of the United States and found that intrabasin tectonics and sea-level changes have a profound influence on sedimentation patterns and geographic distribution of major unconformities.

Caldwell (1984) and Stott (1984) summarized existing data for the upper Jurassic and Cretaceous and compared the transgressive and regressive cycles of Kauffmann (1977) and global relative changes in coastal onlap of Vail et al. (1977) to transgressive and regressive cycles identified in the Canadian Rocky Mountains and interior plains. In addition to matching Kauffman's third order cycles, three Aptian to Albian fourth order transgressive-regressive cycles are recognized. These latter may be distinguished not only by more limited geographic extent, but also by less well differentiated facies suites, shorter duration and the probability of being controlled by local or regional tectonics (Fig. 9).

The above discussion suggests that both global and regional considerations must be considered when evaluating mechanisms responsible for sea level fluctuations and the resulting shoreward-basinward shift in the strandline during Cretaceous time. Equilibrium exists between absolute changes in sea level and sediment supply, regional and local tectonism, subsidence rates and climatic variations. The result of these factors is a relative change in sea level; inferring that geographically extensive events may be controlled by eustatic changes and smaller local and regional events may be controlled by tectonics and other factors but are normally overprinted with eustatic fluctuations.

The controlling elements of eustatic sea-level fluctuations may be difficult to determine in tectonically active basins. Kauffman (1984) linked active plate movements with periods of regional tectonic activity marginal to and in the Western Interior Foreland Basin. The Bluesky Formation was deposited during the transgressive phase of a third-order eustatic cycle lasting between three to nine million years (Fig. 10). However, local tectonic, climatic, or sedimentologic processes probably influenced the depositional style (Caldwell, 1984; Stott, 1984; Weimer, 1984). Small scale progradation of the Bluesky Formation sediment during the third-order transgression may be attributed to fourth-order cyclicity, representing eustatic still-stand events.

2.3.0. PALEOGEOGRAPHY

Within northeastern British Columbia, the late Barremian-early Aptian age Sikanni Chief delta prograded into the Moosebar Sea, fed by the Spirit River and Edmonton paleodrainage systems (Fig. 11). Sandstone, siltstone, and coal deposits of the Sikanni Chief delta complex interfingered northward with nearshore, shallow marine, and offshore sandstones, siltstones and mudstones.

During late Aptian to earliest Albian time, Sikanni Chief delta was flooded by the southward transgression of the Moosebar Sea. In northeastern British Columbia, marine waters eventually inundated the foreland trough containing Spirit River and Edmonton paleovalleys. These paleodrainage systems eventually were filled with brackish-water and estuarine sediments representing the leading edge of the transgression.

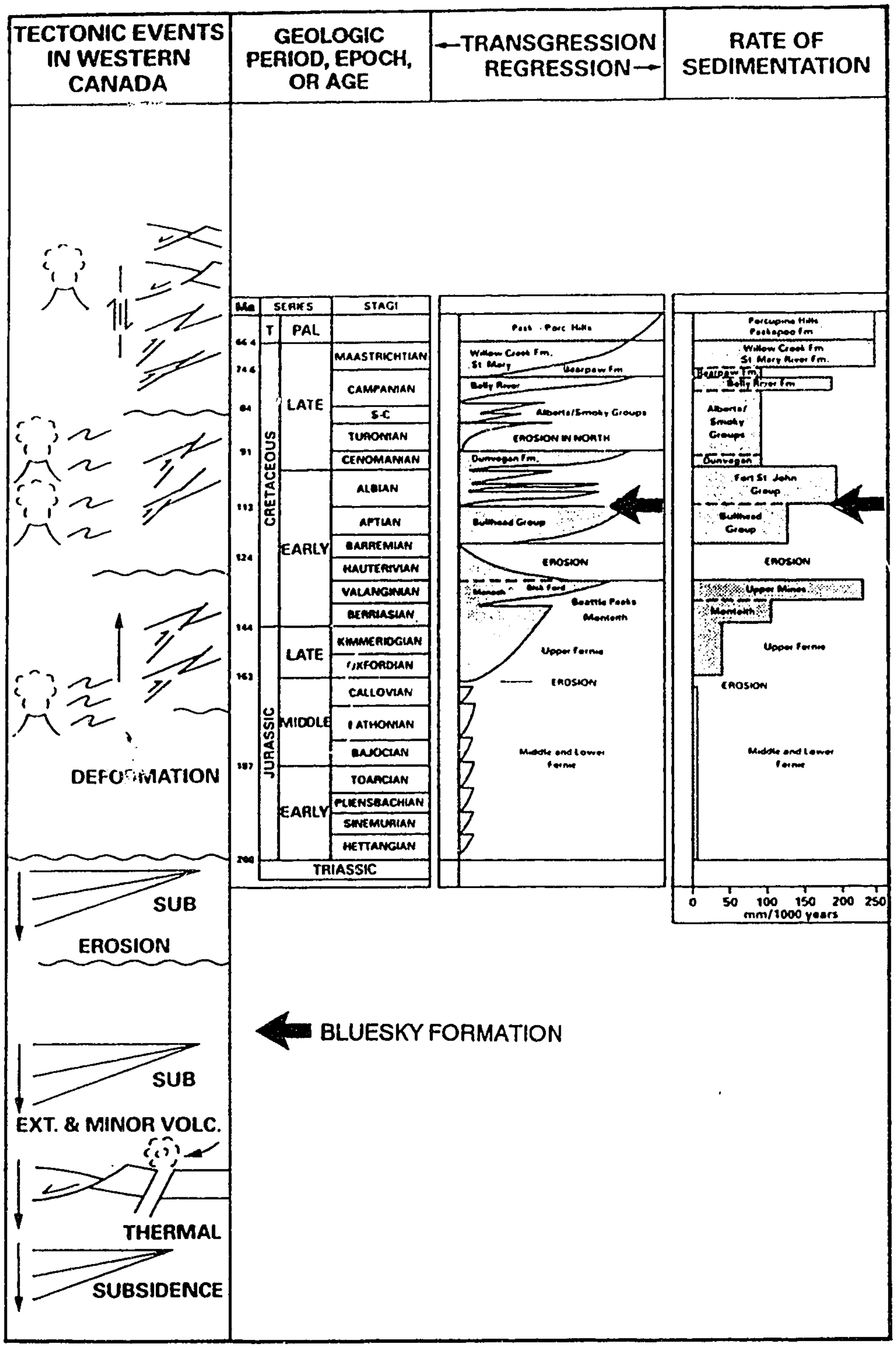


Figure 10. Tectonic events in Western Canada, and depositional events in the foreland basin (modified from Fermor and Moffat, 1992).

Early Albian Bluesky time is marked by continued transgression of the Moosebar Sea southward across the Western Interior along pre-existing paleovalleys (Fig. 12). In the Peace River region of northeastern British Columbia, sediment continued to be supplied seaward, sourced from adjacent uplifted regions (Caldwell, 1984). Volcanic activity in the Western Cordillera is indicated by the abundant volcanic detritus and clays present within Bluesky equivalents in southern Alberta (Leckie and Smith, 1992). The transgression is represented by the continued subsidence of the Moosebar basin and continued increased rise of relative sea-level pushing southward into Alberta. Bluesky deposits reflect deposition in retrogradational shoreface and marginal marine environments. High frequency sea-level fluctuations produce Bluesky incised valleys, fluvial-estuarine valley-fill sequences and local progradational strandlines.

Early Albian Buckinghorse Formation and time equivalents record the reworking of the Bluesky shoreline trend into a thin, regional basal lag during continued transgression. This eventually results in deep water sediments accumulating in an open marine environment. It is during maximum transgression that the Moosebar Sea completely floods the Western Interior, leaving only isolated islands exposed in southern Alberta and Saskatchewan.

The source of Cretaceous sediments was probably derived from the rising western hinterland and the low-lying islands (i.e. Keg River, Red Earth and Wainwright Highlands) separating the Gething and McMurray-Clearwater Troughs (Price and Mountjoy, 1970; Stott, 1973; 1982).

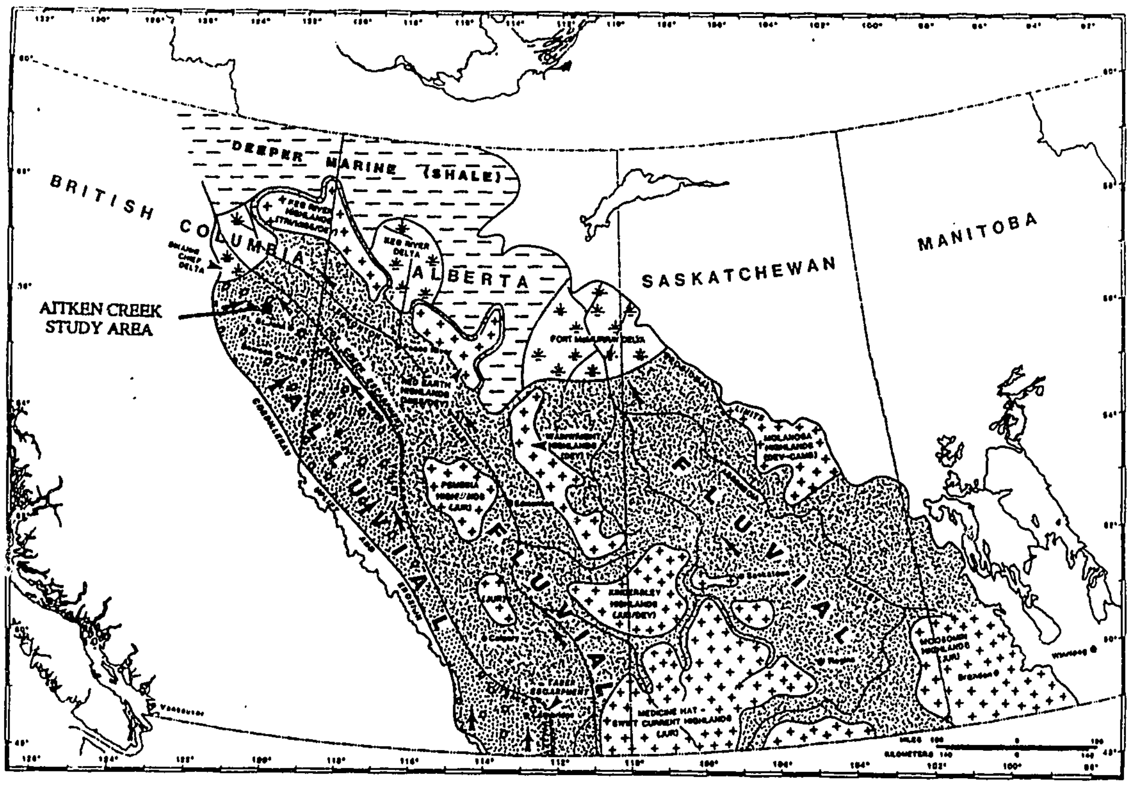


Figure 11. Paleogeographic reconstruction of the Cadomin, Ellerslie, Gething, and Dina Formations (modified from Leckie and Smith, 1992).

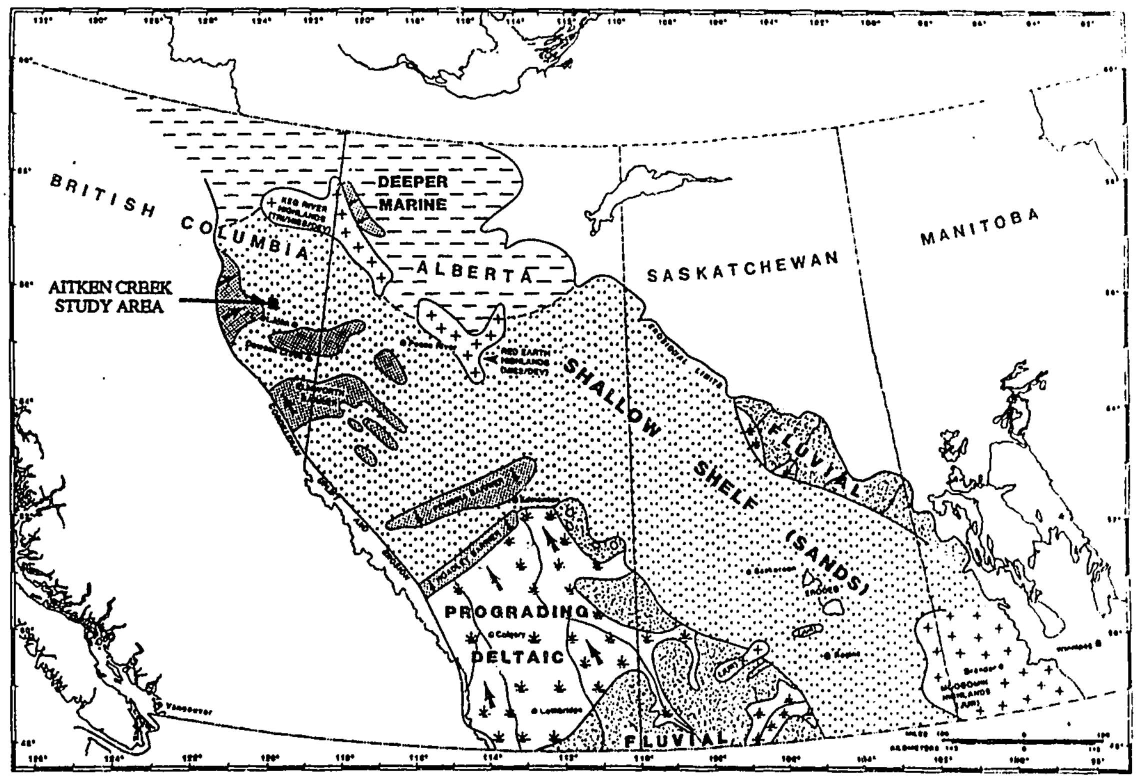


Figure 12. Paleogeographic reconstruction of the Bluesky, Glauconite, Wabiskaw, and Lloydminster Formations (modified from Leckie and Smith, 1992)

The main source of sediments for the Fort St. John Group, which includes the Bluesky Formation, was also from the uplifted western hinterland (Stott, 1982). The Columbian orogeny began in the southern section of the Omenica Crystalline Belt in late Jurassic time and culminated in the mid-Tertiary as an early Larimide event. Wedges of Fort St. John Group strata thicken westward and record the tectonic movement of the Crystalline Belt and the associated development of the early stages of the Rocky Mountain thrust belt (Stott, 1982). Chert pebbles from the Bluesky Formation, at Aitken Creek, are interpreted to be derived from Paleozoic, upper Carboniferous, Triassic and Jurassic sediments from western source areas.

Paleomagnetic and plate reconstructions along the western margin of the North American craton (Wilson *et al.*, 1992) places the study area at approximately 40 to 45 degrees North of the paleoequator during Aptian time

Climatic conditions during the Lower Cretaceous are generally considered to have been warm and humid, during a period experiencing global greenhouse conditions. This is infered from the types of macro and micro-flora observed in cores from the Gething Formation and previous studies (Stott, 1973; 1982). Carbonaceous siltstones and mudstones within this study contained abundant *Podozamites lanceolatus* with modern representatives presently located in the southern hemisphere in sub-tropic environments (C.R. Stelck, pers. comm., 1994). Leckie and Smith (1992) report that extensive coals deposits within the Gething and Gates Formations formed in a warm, humid-maritime setting along and inland of the coast in northeastern British Columbia and northwestern Alberta.

3.0.0. STRATIGRAPHY

3.1.0. GETHING FORMATION, AITKEN CREEK STUDY AREA.

The Aptian-earliest Albian Gething Formation is a heterogeneous stratigraphic unit consisting of coals, carbonaceous siltstones and mudstones, micaceous sandstones and chert pebble conglomerates. Gamma-ray log character is variable. The sonic log signature displays an open serrated character illustrating the abundant coal and carbonaceous siltstone and mudstone interbeds (Fig. 13). The Gething Formation is 75 m thick at Aitken Creek (Fig. 6), and locally thins as a result of incision of the Bluesky valley and/or basement fault reactivation to approximately 50 m. Outside of Aitken Creek, the Gething Formation thickens to the west and thins to the north and east. The contact with the underlying Buick Creek Formation is conformable; where the Gething Formation overlies shales and siltstones of the Fernie Group, the contact is unconformable. The Gething is disconformably overlain by fluvial conglomerates, estuarine sandstone and mudstone, and shoreface sandstones and pebbly conglomerates of the Bluesky Formation.

Controversy persists regarding the age of Gething Formation sediments within the Western Canada Sedimentary Basin. Palynomorphs identified within this study (Table 2) and dated by Dr. Jan Ford and Dr. C.R. Stelck suggest Late Aptian age for Upper Gething deposits in the Aitken Creek area, and are generally comparable with recent results based on macro- and microfauna (Gibson, 1992).

3.2.0. BLUESKY FORMATION, AITKEN CREEK STUDY AREA.

The Bluesky Formation represents the earliest Albian sedimentation within the Fort St. John Group, and is based on the absence of significant coal horizons, differentiating it from the underlying Gething Formation (Gibson, 1992). In the study area the Bluesky Formation consists of silty carbonaceous mudstones, carbonaceous siltstones, quartz sublitharenite, and clast- and matrix-supported polymodal, bimodal, and rare unimodal, chert pebble conglomerate. Gamma-ray log characteristics display sharp-based, smooth and serrated cylinder, bell and funnel shaped profiles with gradual bases and abrupt upper contacts. The sonic log character is dominated by tight or smooth linear shapes (Fig. 14). The thickness of the Bluesky Formation changes rapidly over short distances, ranging from 2.0 to 37 m in Aitken Creek (Fig. 6). Similar thickness trends are observed within the rest of the study area, with maximum thicknesses of up to 15 m adjacent to Aitken Creek. The Bluesky Formation disconformably overlies lower detla plain coals, mudstones, siltstones and fine-grained sandstones of the Gething Formation and is disconformably overlain by matrix-supported conglomerates, pebbly sandstones, bioturbated muddy sandstones and shaley mudstones of the Buckinghorse Formation. Internally, the Bluesky Formation is subdivided by numerous marine flooding surfaces and ravinement surfaces.

In the absence of diagnostic index fossils, only approximate ages can be infered for the Bluesky Formation based on stratigraphic position and lateral

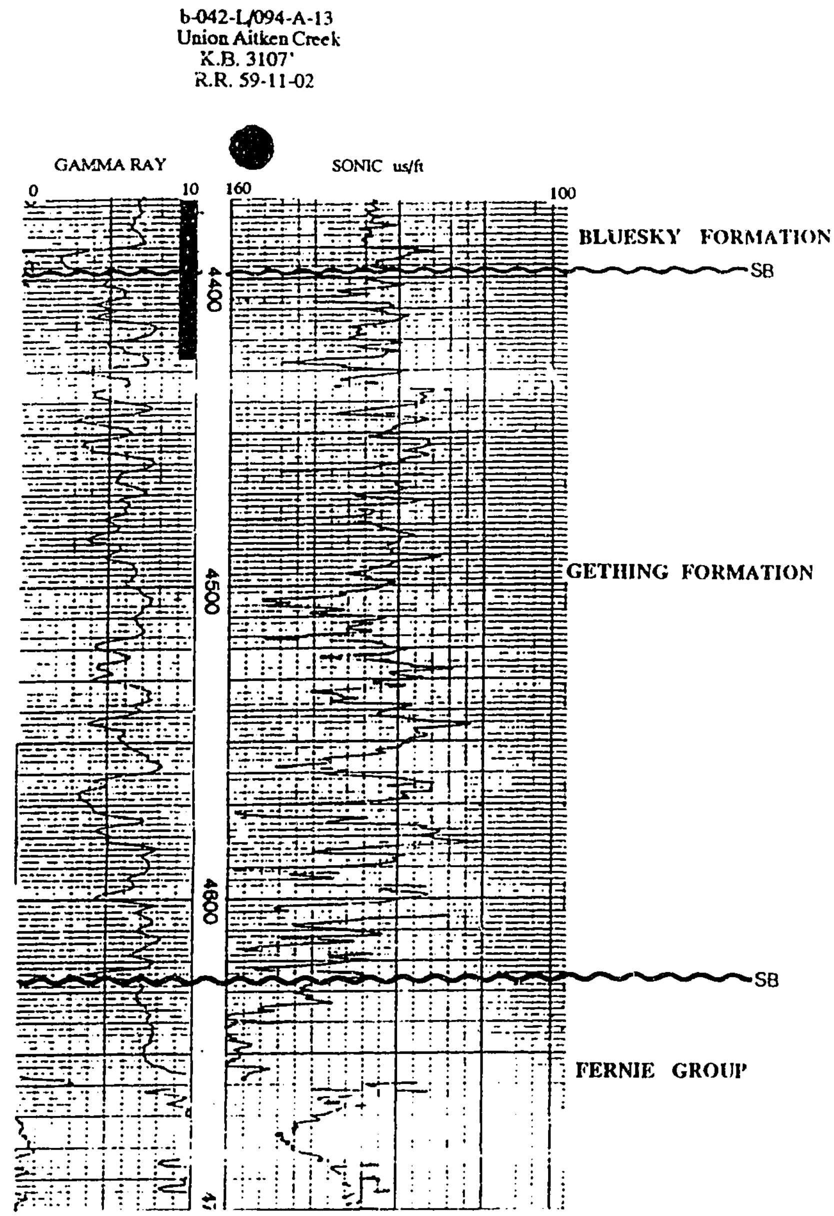


Figure 13. Representative Gething Formation gamma ray-sonic well log response. In this well, the Gething Formation and Fernie Group are separated by a third-order sequence boundary (SB). This third-order sequence boundary separates the overlying Mannville Group clastic wedge from the underlying Kooteney-Fernie clastic wedge. Cored interval represented by black vertical bar. Core description shown in Appendix A.

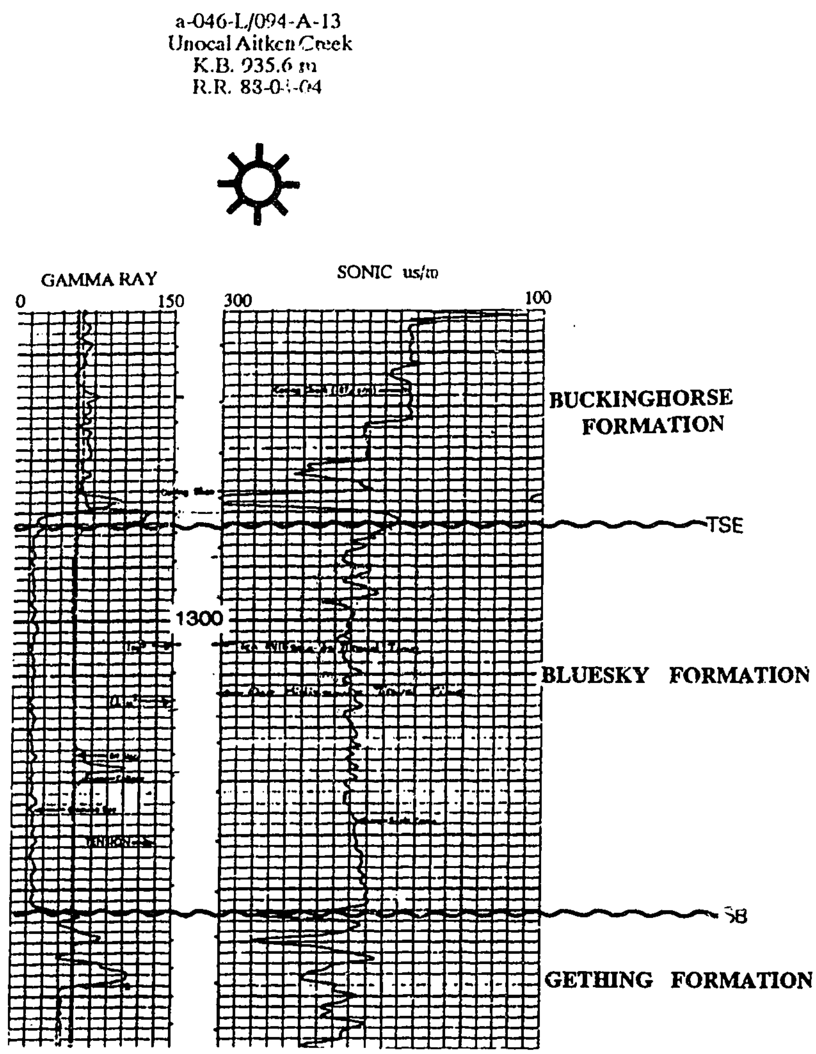


Figure. 14. Representative Bluesky Formation incised valley fill gamma ray-sonic well log response from the Aitken Creek Field. In this well, the Bluesky Formation and Gething Formation are separated by a fourth-order sequence boundary (SB). The top of the Bluesky Formation is defined by a transgressive surface of erosion (TSE) interpreted as a *wave ravinement surface.*

stratigraphic associations. In the Bullmoose Mountain and Tetsa River areas of northeastern British Columbia, the early Albian microfaunal biostratigraphic assemblage zone 5 of Stott (1973) can be assigned to the Bluesky Formation (Fig. 14) (Stelck, pers. comm., 1993). In the Peace River Plains, Caldwell (1984) assigned the Bluesky Formation to the early Early Albian *Cleoniceras subbayleyi* ammonite zone. *Cleoniceras* was identified in the basal Loon River shales by Stelck *et al* (1956) in the Alberta Peace River Plains. Mellon and Wall (1956) were able to correlate equivalents of this microfaunal zone into Pine River Area, northeastern British Columbia within the basal shales of the Moosebar Formation. Therefore, the Bluesky Formation is no older than early Early Albian *Rectobolivina* sp. subzone and no younger than lower *Trochammina mcmurrayensis* subzone. Palynomorphs dated within the Aitken Creek area by J. Ford (1994) infer an Early Albian age for the Bluesky Formation (Table 2), and have subsequently been confirmed by C.R. Stelck (pers. comm., 1994).

3.3.0. BUCKINGHORSE FORMATION, AITKEN CREEK STUDY AREA.

The early Albian Buckinghorse Formation, consists of matrix-supported conglomerates, pebbly sandstones, bioturbated muddy sandstones and dark grey shaley mudstones. Its gamma-ray and sonic log character is open or tighlty serrated linear shaped (Fig. 16). The Buckinghorse Formation disconformably overlies the Bluesky Formation. This contact is characterized by a wave ravinement surface which is overlain by a 0.6 to 2.0 m thick unit of matrix-supported conglomerates, pebbly sandstones, and bioturbated muddy sandstones representing a transgressive lag (Fig. 6).

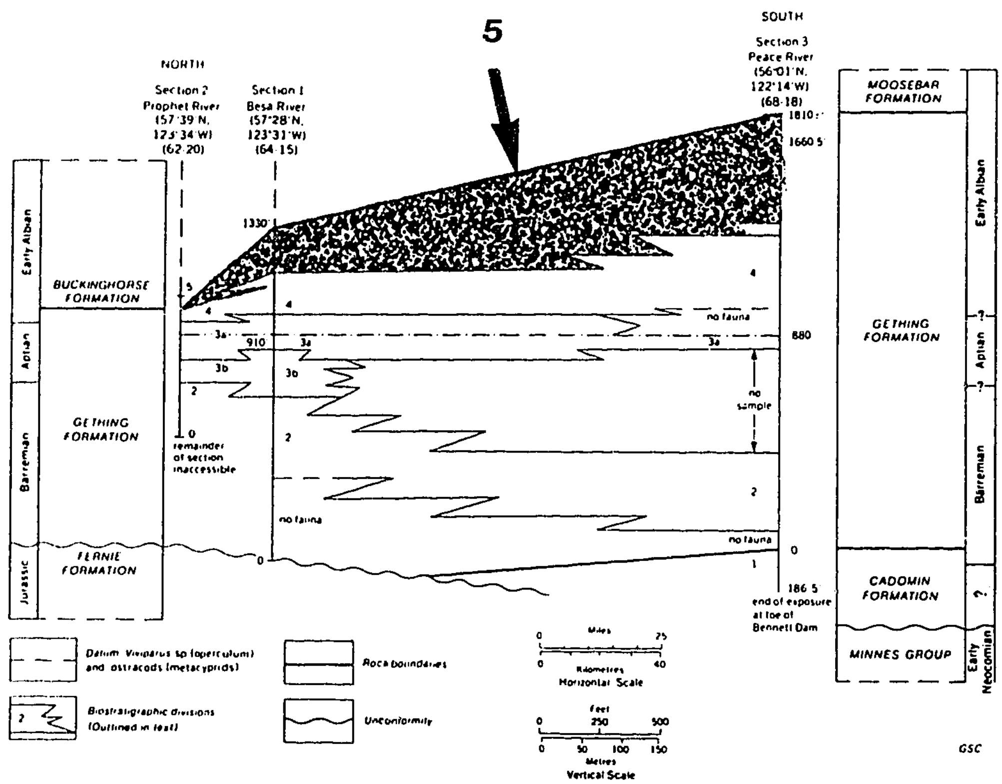


Figure 15. Biostratigraphic divisions of the Gething, Bluesky, and Buckinghorse Formations, northeastern foothills, British Columbia (modified from Stott, 1973).

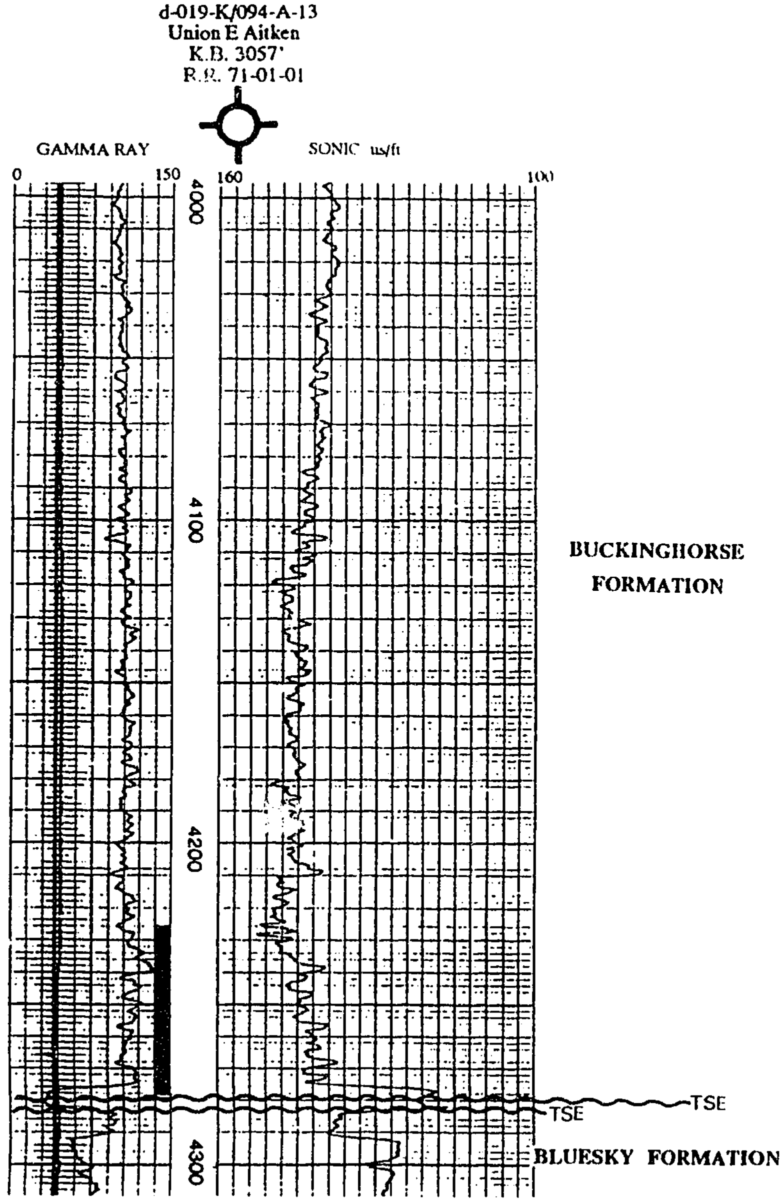


Figure 16. Representative Buckinghorse Formation gamma ray-sonic well log response. In this well, the Buckinghorse Formation and Bluesky Formation are separated by a transgressive surface of erosion (TSE) interpreted as a *wave ravinement surface* . Cored interval is represented by a black vertical bar. Core description is shown in Appendix A.

This transgressive lag is conformably overlain by open marine shaley mudstones representing abrupt deepening during the Moosebar marine transgression.

The Buckinghorse Formation and lateral equivalents of the Moosebar Formation and Bullmoose Members in northeastern British Columbia contain macro- and microfaunal evidence compatable with an early Albian age (Gibson, 1992).

The various sources of biotstratigraphic zonations suggest that sediments of the lower Middle Mannville Group of Alberta were deposited later than Bluesky Formation sediments within the Peace River Area. This implies the transgression of the Moosebar/ Wilrich Sea from the north into southern Alberta was diachronous.

4.0.0. SEDIMENTARY FACIES

Using a process sedimentological approach as described by Siemers and Tilman (1981), sedimentary facies are recognized by internal features such as lithology, nature of bounding contacts, primary physical and biological sedimentary structures, secondary soft sediment deformation features, post-depositional diagenetic features, sediment texture, sediment composition, and palynology. The following section contains sedimentologic descriptions and interpretations of a variety of facies identified from the Gething, Bluesky and Buckinghorse Formations. These facies are the framework for facies associations used in the development of a depositional model for the Aitken Creek Field.

4.1.0. GETHING FORMATION SEDIMENTARY FACIES

Eight facies identified from the Gething Formation are all interpreted to be of delta plain origin. All facies are part of the lithostratigraphic Gething Formation within the study area. These facies are labelled 1 through 5, with subdivisions given an alphabetic subheading. The interpretation of the various facies within the lithostratigraphic Gething Formation are comparable to modern and ancient environments identified by Elliott (1974; 1976; 1986), Coleman and Prior (1982), Moslow and Tillman (1986), Bhattacharya and Walker (1991), Gibson (1992), and Pemberton and Wightman (1992; 1994). The Gething Formation delta plain facies sedimentary characteristics and interpretations are summarized in table 4 and illustrated in plates 1, 2, and 3.

4.1.1. GETHING FORMATION FACIES SUMMARY

Interdistributary bay facies (Table 4) consist of bioturbated silty mudstones, lenticular and wavy bedded fine-grained sandstone and mudstones (Plates 1, 2). Fine-grained sandstone laminae and beds are sharp-based, parallel, or ripple laminated. Lenticular to wavy bedded fine-grained sandstones and mudstones contain sections which are strongly burrowed. The upper sections of interdistributary bay facies commonly are rooted.

Primary sedimentary structures of interdistributary bay facies infer both suspension deposition and bedload traction currents (unidirectional and oscillatory). Trace fossils consist of a low diversity, but moderate to high density assemblage of deposit-feeders interpreted as a brackish-water assemblage, similar to assemblages identified by Pemberton and Wightman (1992).

Crevasse splay facies (Table 4) interfinger with interdistributary bay facies, and consist of lenticular and wavy bedded fine-grained sandstone and mudstone, overlain by sharp- or scoured based, climbing ripple cross-laminated, plane laminated, and massive bedded fine- to very coarse-grained sandstone (Plate 2, 3). Primary sedimentary structures are moderate- to poorly preserved; usually displaying soft sediment deformation features or strongly burrowed. Crevasse splay facies coarsen in grain-size and increase in sandstone content upwards, with the uppermost deposits becoming weak to moderately rooted.

Primary sedimentary structures comprising crevasse splay facies infer deposition by both suspension deposition and lower flow regime bedload traction currents, interbedded with sediments deposited rapidly from suspension and/ or transported by upper to lower flow regime unidirectional currents. Trace fossils are characterized by a brackish-water assemblage, similar to those identified by Pemberton and Wightman (1992).

Channel-fill facies (Table 4) become progressively fine-grained and decrease in sandstone content upwards, consist of massive matrix-supported conglomerate and coarse- to fine-grained trough crossbedding, plane laminations, climbing ripple cross-laminations, and wavy- to lenticular bedding (Plates 2, 3). Burrowing is moderate to weak. Trace fossils are characterized by a low density and diversity assemblage of suspension- and deposit-feeders.

Channel-fill facies infer upper to lower flow regime unidirectional currents, with the upper sections of the facies experiencing both suspension deposition and lower flow regime transport of sediments. Trace fossils represent the *Skolithos* ichnofacies within upper- to lower flow regime deposits and a brackish-water assemblage where both suspension deposition and lower flow regime transport of sediments occurs.

Marsh or swamp facies (Table 4) consist of highly carbonaceous mudstones and coal beds (Plate 3). These deposits infer suspension deposition, anoxia, and highly vegetated substrates within the Gething delta plain.

Table 4. Summary of sedimentary characteristics within sedimentary facies, Gething Formation, Aitken Creek area, British Columbia.

Facies	Lithology	Thickness	Bedding Features	Physical Sedimentary Structures	Biogenic Sedimentary Structures	Sedimentary Processes	Depositional Environment
1	Silty mudstone	0.4-2.2 m	Sharp based; normal grading; rare synaeresis cracks	Massive appearing; Planar and starved (Current & Wave) ripple laminations; local intensly bioturbated units; soft sediment deformation features	*Asterosoma* *Teichichnus* *Terebellina* *Thalassinoides* *Chondrites* *Planolites* *Gyrolithes* *Palaeophycus* Rhizoliths rootlets	Suspension depositon Rare lower flow regime undirectional and oscillatory traction currents	Interdistributary bay Abandoned Distributary Channel Natural Levee
2	Sandstone, Siltstone & Mudstone	0.15-2.0m	Sharp or erosional, gradational or bioturbated lower & upper contacts; load contacts, rare microfaulting; soft sediment deformation, flame structures features; normal grading; siderite beds, pyrite and synaeresis cracks; Fining and coarsening upward sequences	Horizontal, lamination; Current and wave ripple cross-lamination; Climbing ripple cross-lamination; lenticular, wavy and flaser bedding.	*Teichichnus* *Palaeophycus* *Planolites* *Chondrites* *Skolithos* *Thalassinoides* *Terebellina* rootlets	Both suspension depositon and lower flow regime bedload traction currents (unidirectional and oscillatory) Rapid depositon from suspension	Distributary pointbars; Interdistributary bays Crevasse Spaly
3A	Fine- to coarse -grained sublitharenite sandstone	0.5-2.4m	Sharp & scoured bases with mudstone rip-ups & coal intraclasts ; fining and coarsening upward sequences	Trough and planar tabular cross-bedding	*Skolithos* *Palaeophycus*	Lower flow regime unidirectional traction currents	Distributary & crevasse channel
3B	Fine- to medium grained quartz arenite sandstone	0.30-0.80m	Sharp & scoured surfaces; mudstone rip-ups & coal intraclasts; fining upward sequences	Small scale trough cross-bedding, Climbing ripple cross-lamination; Plane lamination	*Palaeoph*_ *us* rare rootlets	Upper to lower flow regime unidirectional traction currents Rapid deposition from suspension	Crevasse Spaly Crevasse Channel Distributary Point bar
3C	Fine- to medium grained quartz arenite sandstone	Upto 0.5m	Sharp based	Sub-horizontal plane lamination. normal graded laminae.	*Palaeophycus*	Upper flow regime unidirectional traction currents	Distributary Channel
3D	Fine-grained to granular, quartz arenite and sublitharenite sandstone	0.05-0.60m	Soft sedimnet deformation; Fining upward sequences.	Massive, rare cross-bedding	*Palaeophycus*	Upper flow regime traction currents Reworking by lower flow regime oscillatory and unidrectional currents	Distributary channel Crevasse Splay
4	Matrix-supported intraclast conglomerate	0.1-0.3m	Gradational & erosive bases; rare clast imbrication; no chert pebbles; Fining upward sequences	Massive Crude cross-bedding	None	Upper flow regime unidirectional traction currents	Distrubuary or crevasse channel lag
5	Coal & Carbonaceous Mudstone	Upto 1.5 m	Sharp upper and lower contacts; normal grading; high carbon content; fossilized leaf impressions and branches	Parallel laminations, wavy and lenticular bedding; massive bedding; soft sediment deformation	abundant rootlets *Planolites* *Chondrites* Rare *Teichichnus* & *Palaeophycus*	Suspension deposition interupted by high energy lower flow regime traction currents.	Marsh - Swamp

Plate 1.

A. Facies 1, Interdistributary bay massive silty mudstone with large rhizolith (Rz) replaced by pyrite. Location: b-022-C/094-H-4, 1273.5-1273.8m

B. Facies 1, Interdistributary bay massive silty mudstone. Location: b-022-C/094-H-4, 1276.5-1276.7m

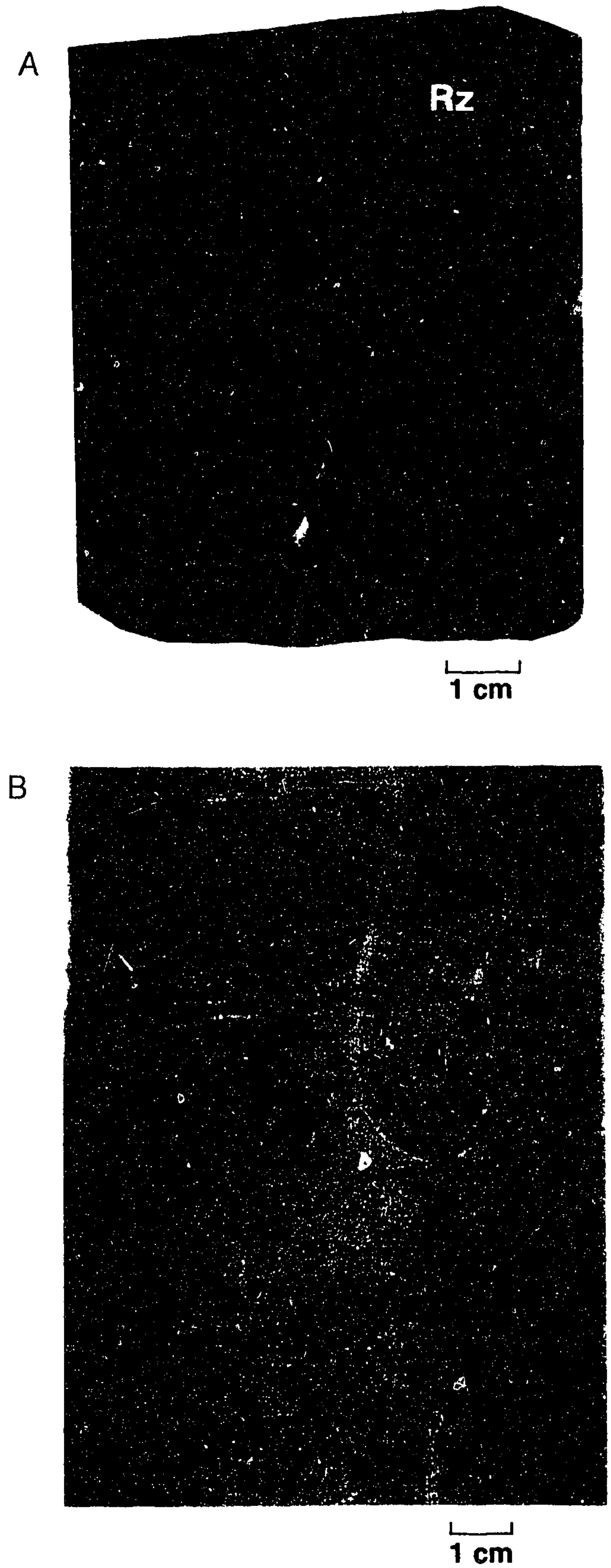

A
Rz
1 cm
B
1 cm

Plate 2.

A. Burrowed, interbedded sandstone, siltstone and mudstone of Facies 2, Interdistributary bay. Biogenic structures are *Palaeophycus* (Pa), *Planolites* (Pl), & *Chondrites* (Ch). Synaeresis cracks are rare (Sya). Location: d-023-L/094-A-13, 1324.0-1324.25m.

B. Soft sediment deformation features within Facies 2, Interdistributary bay. Location: d-099-C/094-H-4, 1282.0-1282.25m.

C. Local bioturbated units within Facies 2, Interdistributary [illegible] splay. Biogenic structures are *Gyrolithes* (Gy), *Palaeophycus* (Pa), *Planolites* [illegible]*ndrites* (Ch). Rootlets (arrow and R) are present below load contact of [illegible] medium-grained crevasse splay sandstones. Location: c-028-F/094-A-13, [illegible]90.5m

D. Cross-stratified sandstones of Facies 3A. Photograph shows trough cross-bedding with sideritized mudstone rip-up clasts along laminations.
Location: d-071-I/094-B-16, 4273'-4273'3".

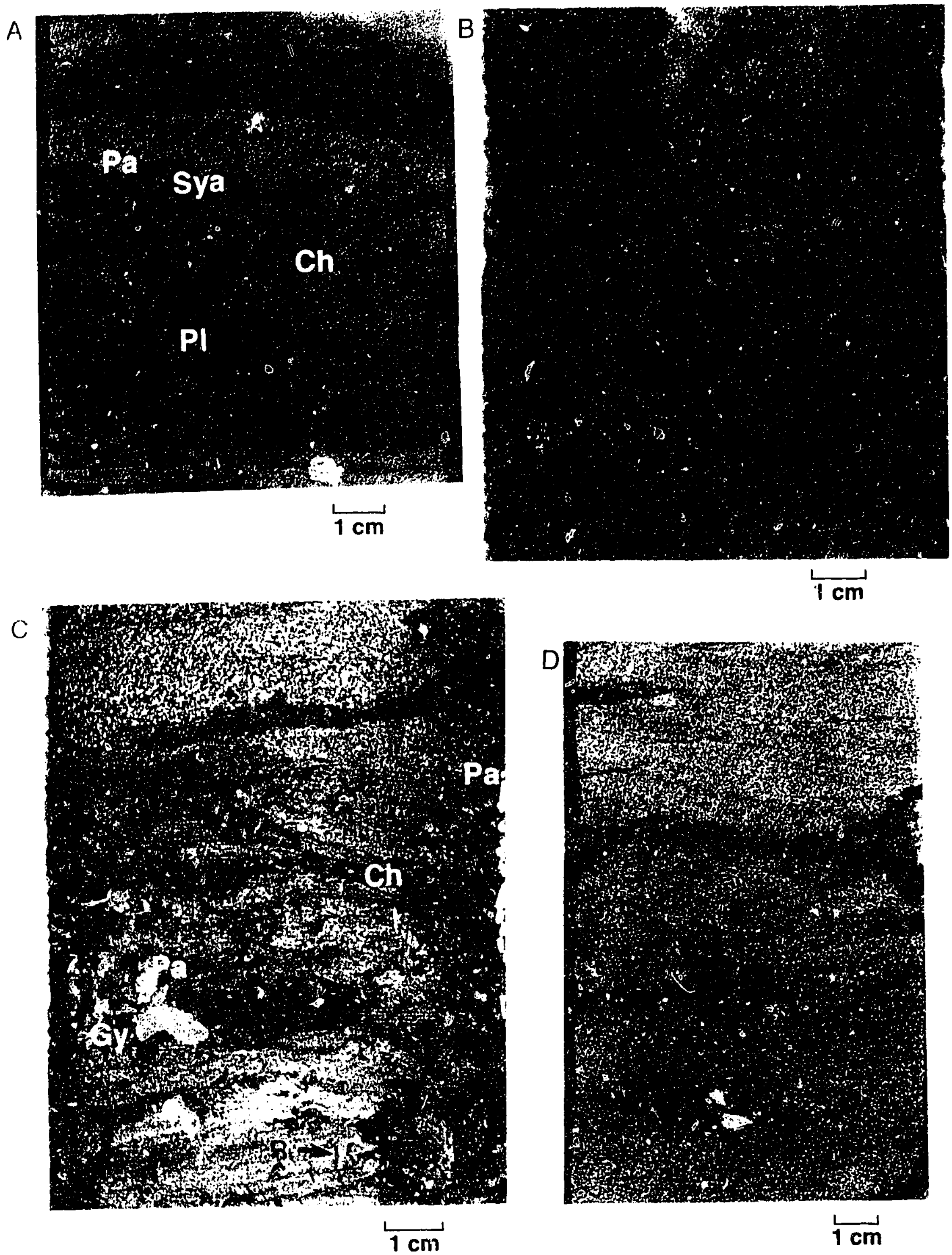

A
Pa
Sya
Ch
Pl
1 cm
B
1 cm
C
Pa
Ch
Pa
Gy
1 cm
D
1 cm

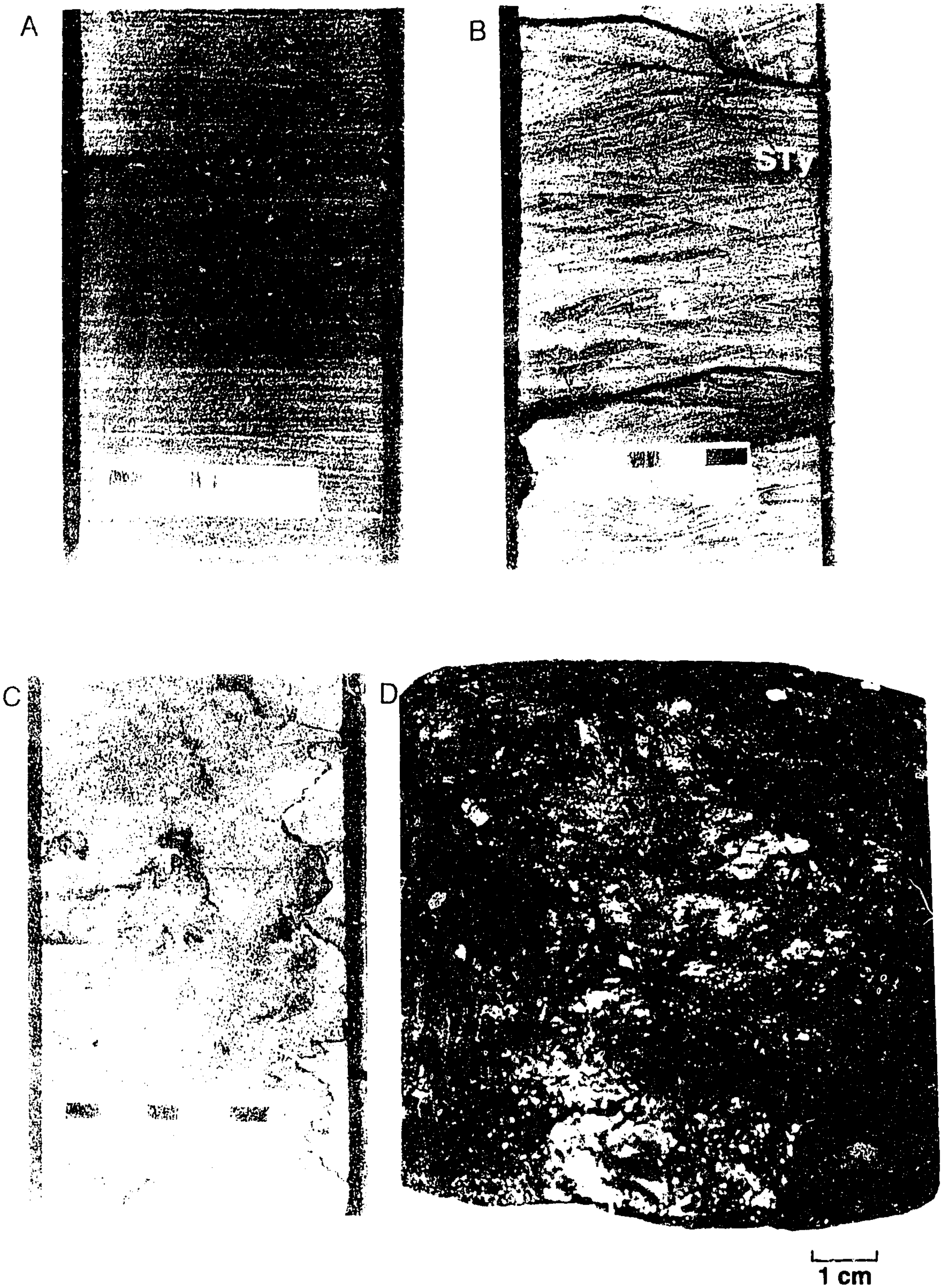
Plate 3.

A. Parallel laminated sandstone of Facies 3C, Distributary or crevasse channel-fill Location: d-023-L/094-A-13, 4308'-4308'3".

B. Small-scale cross-ripple laminated sandstones of Facies 3B, Crevasse splay/channel. Styolites (STy) and rootlets (G) are present in the photograph. Location: d-021-L/094-A-13, 1320.1-1320.3m.

C. Massive sandstone of Facies 3D, Distributary channel and crevasse splay environments. This photograph shows Facies 3D to be intensely bioturbated with only a few biogenic structures that can be identified. Biogenic structures are *Terebellina* (T) and *Palaeophycus* (Pa). Note the vertical styolite (STY) running the length of the core photo. Location: d-023-L/094-A-13, 4335'-4335'3".

D. Coal and carbonaceous mudstone of Facies 5, Marsh-swamp environments. Location: b-022-C/094-H-4, 1269.1-1269.4m.


A
B
STy
C
D
1 cm

4.2.0. BLUESKY FORMATION SEDIMENTARY FACIES

The following section contains descriptions and sedimentologic interpretations of twelve facies and four subfacies identified in this study within the lithostratigraphic Bluesky Formation. These facies are labelled 1 through 5, with subdivisions given an alphabetic subheading. Facies descriptions and interpretations are summarized in Table 5.

4.2.1. FACIES 1 — MASSIVE SANDY TO SILTY MUDSTONES

DESCRIPTION: Facies 1 (Plate 4A) consists of dark grey, sandy to silty mudstone, with rare (< 10%) millimetre- to centimetre-scaled, very fine-grained, well sorted, planar, silty to sandy starved ripple and parallel laminations, and may locally be intensely bioturbated (60-90%). Bed thickness, and sandstone and siltstone content, decrease upwards. This facies is very carbonaceous and fines upwards and may be over 4 m thick. It contains a low diversity, high density, trace fossil assemblage characterized by *Teichichnus*, *Asterosoma*, *Thalassinoides*, *Chondrites*, and *Planolites*, passing upward into a monospecific assemblage characterized by slightly elliptical shaped, rare *Planolites*. Samples examined for palynomorphs contained a mixed assemblage of poorly preserved terrestrial forms, marine plankton, Dinoflagellates, and common undifferentiated spores (Jan Ford, *pers. comm.*, 1994). The mudstones contain: a) perfectly preserved leaf impressions of ferns and *Podozamites lanceolatus* (Stelck, pers. comm., 1994) on bedding plane surfaces; b) siderite cement as a replacing fabric; and c) pyrite.

INTERPRETATION: The rare occurrences of current or wave structures and the fine-grained nature of this facies infer deposition in an environment prone to suspension

Table 5. Summary of sedimentary features identified in sedimentary facies in the Bluesky Formation, Northeastern British Columbia.

Facies	Lithology	Thickness	Bedding Features	Physical Sedimentary Structures	Biogenic Sedimentary Structures	Depositional Environment
1	Sandy to silty mudstone	0.65->4m	Sharp based	Planar laminations, local intensly bioturbated units	*Asterosoma* *Teichichnus* *Thalassinoides* *Chondrites* *Planolites*	Estuarine-Interdistributary bay, Abandoned Estuarine Channel
2A	Sandstone, Siltstone & Mudstone	0.15-1.5m	Sharp or erosional, gradational or bioturbated lower & upper contacts; Inclined bedding planes, Fining and coarsening upward sequences	Horizontal, lamination; Current and wave ripple cross-lamination; bi-directional ripple cross-laminations, herringbone cross-bedding; lenticular, wavy and flaser bedding	*Teichichnus* *Palaeophycus* *Planolites* *Chondrites* *Skolithos* rootlets (rare)	Estuarine tidal pointbars; initial abandandoned esturaine channels, Tidal flats
2B	Silty to sandy mudstone	0.15-0.6m	Biogenic sedimentary structures may dominate physical ones; coarsening upward sequence	Rare lenticular and wavy bedding, current and oscillatory ripple laminations	*Terebellina* *Teichichnus* *Planolites* *Chondrites* *Palaeophycus*	Restricted bay, Back-barrier lagoon
3A	Fine- to coarse -grained quartz arenite to litharenite	0.5-2.4m	Sharp & scoured bases with chert pebble lag, mudstone rip-ups, Tidal bundles; fining and coarsening upward sequences	Trough and planar tabular cross-bedding	*Diplocraterion* *Teichichnus* *Palaeophycus*	Estuarine channel fill, Subtidal shoal deposit
3B	Fine- to medium grained litharenite	0.30-0.80m	Sharp & scoured surfaces	Small scale trough cross-bedding, ripple cross-lamination; Plane lamination	*Palaeophycus*	Upper shoreface, Outer estuary shoals, Marginal ebb-tidal delta
3C	Fine- to medium grained sublitharenite	0.3-1.5m	Sharp based, normal graded laminae	Sub-horizontal plane lamination	*Palaeophycus* *Ophiomorpha*	Estuarine shoal
3D	Fine-grained to granular, sublitharenite to litharenite and pebbly sandstone	0.05-0.60m	Soft sedimnet deformation; Fining upward sequences.	Massive, rare cross-bedding	*Palaeophycus*	Active estuarine channel fill
3E	Muddy sandstone	0.4-1.22m	Biogenic sedimentary structures may dominate physical ones	None	*Chondrites* *Palaeophycus* *Terebellina* *Helminthopsis* *Teichichnus* *Skolithos*	Transgressive sheet sands or sand shoals, Active estuarine channel fill
3F	Fine-to very coarse-grained quartz litharenite and sublitharenites	> 4m	Scoured contacts clast imbrication Soft sediment deformation; Fining upward sequences	Low-to high angle bedding, trough cross-bedding & horizontal bedding	*Palaeophycus*	Fluvial channel fill, Active estuarine channel fill
4A	Clast-supported chert pebble conglomerate	< 15.0m	Sharp & erosional bass; rare clast imbrication; Fining upward sequences	Low to high angle cross-stratification	None	Fluvial channel fill
4B.1	Martrix-supported chert pebble conglomerate	0.1-0.3m	Gradational & erosive bases; rare clast imbrication Fining upward sequences	Massive Crude cross-bedding	*Glossifungites* ichnofacies below erosional contact	Transgressive shoreface lag, channel lag & channel floor
4B.2	Martrix-supported chert pebble conglomerate	0.4-0.8m	Sharp or Gradational based; normal grading; Fining upward sequences	Low angle & low-to high angle cross-stratification	None	Transgressive shoreface, Fluvial lateral accreting bar
5	Coal & Carbonaceous Mudstone	Up to 20 cm	Sharp upper and lower contacts; normal grading; high carbon content;	massive appearing	abundant rootlets *Planolites*	Marsh - Swamp

sedimentation. Parallel and starved ripple laminations reflect fluctuations in sediment supply. Very fine-grained sandstones represent relatively infrequent, higher velocity episodic currents which deposit the sediment load by traction upon a muddy substrate. Starved ripples could represent sands reworked by shoaling waves or by tidal currents.

Biogenic structures are dominated by a low diversity, and high to low density, assemblage of deposit-feeders and suspension-feeders produced by the feeding habits of annelids and crustaceans. The trace fossil suite is characteristic of a brackish water assemblage, as defined by Ekdale *et al.* (1984), Pemberton and Wightman (1992), Beynon and Pemberton [illegible] and Ranger and Pemberton (1992), and consists of morphologically simple forms, smaller trace fossil forms than their marine counterparts (due to stressed ecological conditions), high trace fossil abundances with low diversity, and a combination of trace fossils from both the *Skolithos* and *Cruziana* ichnofacies. The absence of suspension feeding burrows in the middle portion of this facies is probably due to the low-level of water turbulence, hence little suspended food (Ekdale *et al.*, 1984). The total absence of biogenic structures within the upper sections of this facies infers harsh environmental conditions, likely involving anoxia and/or salinity variations.

The stratigraphic position of this facies suggests that there were temporal changes within the depositional environment. In marginal marine settings, such environments originate by restriction in circulation permitting the deposition of fine-grained material carried in suspension. Palynomorphs, sedimentary structures, and biogenic structures suggest that this facies was deposited in a restricted marine setting, with moderate oxidation and slight anoxia. Similar facies have been interpreted as estuarine/interdistributary bay (Moslow and Tilman, 1986) or abandoned estuarine channel (Rahmani, 1988; Brownridge and Moslow, 1991; Leckie and Singh, 1991), depending on lateral and vertical facies relationships.

4.2.2. FACIES 2A — INTERBEDDED SANDSTONES AND MUDSTONES

DESCRIPTION: Facies 2A (Plate 4B) consists of interbedded sandstone, siltstone, and carbonaceous mudstone up to 1.5 m thick in which bedding plane surfaces can be inclined to angles of 10 degrees or less. Sandstone content within this facies varies between 10 to 50%. Bedsets thin and fine upwards from tens of centimetres to a few centimetres in thickness. Sandstone beds fine upwards from medium- to very fine-grained sandstones with sharp or erosional bases and may contain current- and rare wave-ripple cross-laminations, bi-directional ripple cross-laminations, parallel laminations, and lenticular (symmetrical and assymmetrical) ripples, all of which may contain both continuous and discontinuous mudstone laminations. The sandstone beds may also feature herringbone cross-bedding. Microfaults, stylolites, synaeresis cracks, and load casts are observed. Dispersed chert pebbles (< 2%) along bedding planes occur within the bottom one-third of this facies, and rootlets may be found near the top. The majority of siltstone and sandstone beds are sharp-based with sharp, bioturbated, or rare gradational upper contacts. Mudstones and siltstones contain abundant carbonaceous material and zones of bioturbation. Slickenslide surfaces are commonly observed on carbonaceous mudstone along bedding plane surfaces in the core. Biogenic structures comprise less than 20% of this facies, but finer sediments may be abundantly bioturbated by *Teichichnus, Palaeophycus, Planolites, Chondrites*, and *Skolithos*. Bioturbation within sandstone beds is rare, and usually observed near the top of the bed. The mudstone contains some perfectly preserved leaf impressions of ferns and *Podozamites lanceolatus* on bedding plane surfaces, siderite cement as a replacing fabric, and pyrite.

INTERPRETATION: Ripple cross-laminated beds are interpreted as lenticular, wavy, and flaser bedding (Reineck and Singh, 1980; Allen, 1984) produced by conditions of alternating slack water conditions and tidal current sedimentation (Plate 4B). Mudstone was deposited from suspension fallout draping previously deposited ripple and planar laminated sandstones. Interbedded mudstone laminae and beds represent suspension sedimentation in a low-energy, calm, muddy substrate setting. Sequences that illustrate inclined bedding are interpreted as inclined heterolithic stratification (Smith, 1988). Vertical current bimodality, infered from cross-bedding and cross-laminations, is diagnostic of tidal sedimentation (Smith, 1988). Mud drapes and reactivation surfaces suggest flood-ebb cycles as well as neap-spring tidal variations (Nio and Yang, 1991).

The occurence of rare chert pebbles within the lower portion of this facies indicates that current or wave processes were strong enough to transport these pebbles during flood stage or via storm induced currents. Sandstone beds with loaded contacts suggest deposition over a hydroplastic mud, resulting in unequal loading and vertical re-adjustment at the sand/ mud interface (Reineck and Singh, 1982). Microfaults are interpreted as syn-depositional tension faults which are associated with rapid deposition on a sloping surface.

Rootlet structures occuring near the top of this facies suggest a vegitated and muddy environment existed near the high-water mark. Rootlets are associated with sections that are essentially absent of primary sedimentary structures, similar to observations along the U.S. east coast (Frey and Basan, 1978). Emplacement of rootlet structures is interpreted to have occured within a subaqueous setting based on the lack of subaereal sedimentary features.

Biogenic structures are dominated by a low diversity and moderate- to low density assemblage of deposit-feeders and suspension-feeders. The assemblage of biogenic structures in this facies are interpreted to have occured in physiologically-stressful environments representative of a brackish-water trace fossil assemblage (Ekdale *et al.*, 1984; Pemberton and Wightman, 1992; and Beynon and Pemberton, 1992). In addition to reduced diversity, salinity reduced conditions are inferred by the mixing of both deposit-feeding and dwelling structures (Ekdale *et al.*, 1984). In addition, the presence of synaeresis cracks may suggest an environment influenced by fluctuating salinity (Burst, 1965)

The brackish water trace fossil assemblage, primary sedimentary structures, and bedding characteristics observed here suggest that this facies was deposited in a restricted marine setting, with moderate oxidation, slight anoxia, and alternating current velocities. These features are commonly associated with a variety of estuarine and tidal flat facies (Clifton, 1982, 1983; Wiemer *et al.*, 1982; deMowbray, 1983; Rahmani, 1988; Smith, 1988; Terwindt, 1988).

4.2.3. FACIES 2B — BIOTURBATED, POORLY STRATIFIED SANDSTONES AND MUDSTONES

DESCRIPTION: Facies 2B consists of dark grey-brown, bioturbated, silty to sandy carbonaceous mudstones up to one meter in thickness, with sharp-planar, burrowed, and gradational lower and upper contacts (Plate 4C). The percentage of mudstone is between 40 and 70%. This facies contains partially recognizable beds and physical sedimentary structures, but is more intensely burrowed than Facies 2A. Up to 30% of the primary sedimentary structures may be preserved in the form of lenticular to wavy bedding or (asymmetrical and symmetrical) ripple laminations. Pyrite, siderite, and glauconite occur throughout the facies. Sorting is poor, and is a direct function of the intense bioturbation. Ichnofossils identified within this facies are characterized by horizontal and vertical burrows. Thirty to 90% of the rock may be disturbed by burrow traces characteristic of a low diversity suite consisting of *Planolites*, *Teichichnus*, *Chondrites*, *Palaeophycus*, and *Terebellina*.

INTERPRETATION: This facies is compatable with a low to moderate current velocities, restricted shallow marine, brackish-water environment. Bedding features are interpreted as the product of alternating suspension sedimentation and tidal and/or oscillatory current processes. Mud was deposited during the slack water periods, draping ripple and planar sandstone laminations.

Ichnogenera present are characteristic of the *Cruziana* ichnofacies (Frey and Pemberton, 1984). Pemberton *et al.* (1992) defines the *Cruziana* ichnofacies to include subtidal, poorly sorted unconsolidated substrates, ranging from moderate to low current velocities. Food supplies consist of both suspended and deposited components. Trace makers, therefore, are characterized by suspension feeders, deposit feeders, mobile carnivores and scavengers. Due to lowered current velocities, and abrupt shifts in temperature and salinity, burrows structures associated with this ichnofacies are constructed horizontally within the substrate with only local vertical and subvertical burrows. Beds of densely bioturbated sediments may reflect stable, low current velocity sites within this facies.

Terebellina burrows are smaller and flatter than those observed elsewhere in this study. Their flattened outline and reduced size suggest a restricted, shallow marine subtidal setting (Pattison, 1992). Pattison (1992), who identified *Teichichnus, Terebellina, Planolites,* and *Chondrites* burrows within interbedded sandstones and mudstones from the Viking Formation of central Alberta, has interpreted these features as representing estuarine mudstones (*i.e.,* restricted bays or back barrier lagoons).

4.2.4. FACIES 3A — CROSS-STRATIFIED SANDSTONES, WITH OR WITHOUT MUD COUPLETS

DESCRIPTION: Facies 3A (Plate 4D) consists of normally graded, fine- to coarse-grained, medium grey-brown, quartz arenite to litharenites characterized by trough and planar tabular cross-bedding in beds up to tens of centimetres thick, and bedsets 0.5 to 2.4 m thick. Basal bedsets and/ or bedding contacts are sharp or scoured and are overlain by a coarse lag of chert pebbles or granules, mud rip-up or coal clasts, or carbonaceous material. Mud laminae couplets and drapes occur on sandstone foreset and bottom-set laminations, and may be capped by ripple cross-laminations, which display reactivation surfaces or are disrupted by rare sandstone dykes. Sandstones are generally moderate- to well sorted. Glauconite content averages 1-3%. Cements (2-4%) consist of quartz overgrowths, siderite and authigenic pyrite(?). Bioturbation is weak to moderate (10-40%) and dominated by a low diversity, low to moderate density, assemblage containing *Palaeophycus, Teichichnus, Diplocraterion* and escape traces.

INTERPRETATION: Facies 3A reflects the prevalence of lower flow regime conditions in which unidirectional flow has produced sand wave and dune migration along the sediment water interface by unidirectional oscillatory or tidal currents. Tidal processes in the rock record are recognized by close spatial and temporal current-formed structures indicating bimodal or bipolar flow, abundance of reactivation surfaces in cross-stratification and the presence of primary sedimentary structures which reflect small-scale, repeated alternations in sediment transport conditions (Elliot, 1986; Blatt *et al.*, 1991). Large-scale cross-beds with mud couplets and tidal bundles are interpreted to form during daily tidal cycles (Visser, 1980) and have been described from recent shallow subtidal and intertidal dune bedforms and their ancient counterparts (Allen, 1980a, b; 1981; Homewood and Allen, 1981; Kreisa and Moiola, 1986; Uhlir *et al.*, 1988; Nio and Yang, 1991). Double mud couplets represent mud settling from suspension fallout during the slack periods of the semi-diurnal tidal cycle (Allen and Homewood, 1984; Kreisa and Moiola, 1986; Rahmani, 1988). Reactivation surfaces within the smaller-scale cross-beds suggest time-velocity asymmetry of the tidal current bedload transport, but may also develop during steady or unsteady unidirectional flow (deMowbray and Visser, 1984; Rahmani, 1988). The decrease in size of cross-bedsets up section reflects decreasing flow energy of tidal currents where by sand waves and dunes are replaced by asymmetrical ripples with or without mud drapes.

Within the *Skolithos* ichnofacies, the trace fossil suite is associated with littoral to infralittoral substrates, moderate to relatively high current velocities, large concentrations of suspended food particles, and shifting substrates that are periodically modified by erosion or deposition (Pemberton *et al.,* 1992). Escape traces represent a fleeing behavior due to sudden, catastrophic events. This infers rapid sedimentations rates, the displacement of an organism from its normal habitat into a inhospitable environment, or a drastic environmental change (Ekdale *et al.*, 1984). This facies is interpreted as either an estuarine channel-fill or a subtidal shoal deposit, depending on its occurrence within fining- or coarsening-upward facies associations.

4.2.5. FACIES 3B — RIPPLE-LAMINATED SANDSTONES

DESCRIPTION: Facies 3B is characterized by well sorted, fine-grained, medium to dark grey, litharenites. Beds of small-scale trough cross-bedding, ripple cross-laminations, and low-angle planar laminations characterized by sharp or scoured bases that are covered with rare chert pebbles, and/or angular coal, carbonaceous mudstone, and siderite mudstone intraclasts (Plate 5A). Small-scale trough cross-bedding and ripple cross-lamination sets are tens of centimetres thick and show evidence of combined flow. Small-scale trough cross-beds may contain resedimented organic beds above the scour surface. A complete sandstone bed less than 2 m thick grades upward from small-scale cross-bedding at the base to low-angle planar laminations at the top. Beds of low-angle planar laminations (< 5 degrees) fine upwards, and are tens of centimetres to less than 1.25 m thick.

Biogenic structures are dominated by a moderate to high density, monospecific assemblage identified as *Palaeophycus*. In addition, abundant vertical fractures and styolites disrupt primary sedimentary and biogenic structures. Fine disseminated organic material and quartz overgrowth and siderite cement is present throughout. Accessory minerals include glauconite.

INTERPRETATION: The vertical transition from small-scale trough cross-bedding to low-angle planar laminations implies an increase in current velocities and/or decrease in depth of flow. Low-angle planar laminations may be the product of reworking by high energy unidirectional oscillatory currents (Clifton, 1976). This facies infers deposition by both unidirectional and oscillatory currents, as indicated by low-angle planar cross-beds, small-scale trough cross-bedding, and combined flow ripple cross-laminations. Combined flow ripple cross-lamination is interpreted as transverse combined current/ wave ripples formed where the direction of wave motion is parallel to the axis of current flow (Reineck and Singh, 1980). Such stratification develops near the shoreline, where both current and wave processes are prevalent. The accumulation of organics and mud in the basal scour of small-scale trough cross-beds reflects particles in suspension passing over the crest of the ripple and subsequently settling in the zone of mixing as a result of backflow transport towards the foreset slope and/ or settling in the form of toeset deposits (Reineck and Singh, 1980). This process is most commonly observed in relatively deeper waters, where foresets may trap a considerable amount of suspended load sediment.

The rare to common occurrences of lined biogenic structures suggest an ecologic stressful environment with high sedimentation rates and relatively high energy Due to the high current and/ or wave energy of this facies, little food will be dep therefore, horizontal burrows dominate. This facies is interpreted as being deposit the upper shoreface and consists of shoreface deposits, outer estuary sand shoals an marginal ebb-tidal delta deposits.

4.2.6. FACIES 3C — PARALLEL-LAMINATED SANDSTONES

DESCRIPTION: This facies consists of well sorted, fine- to medium-grained, light grey quartz sublitharenite interbeds, 0.3-1.5 m thick. Basal contacts are sharp and abrupt.

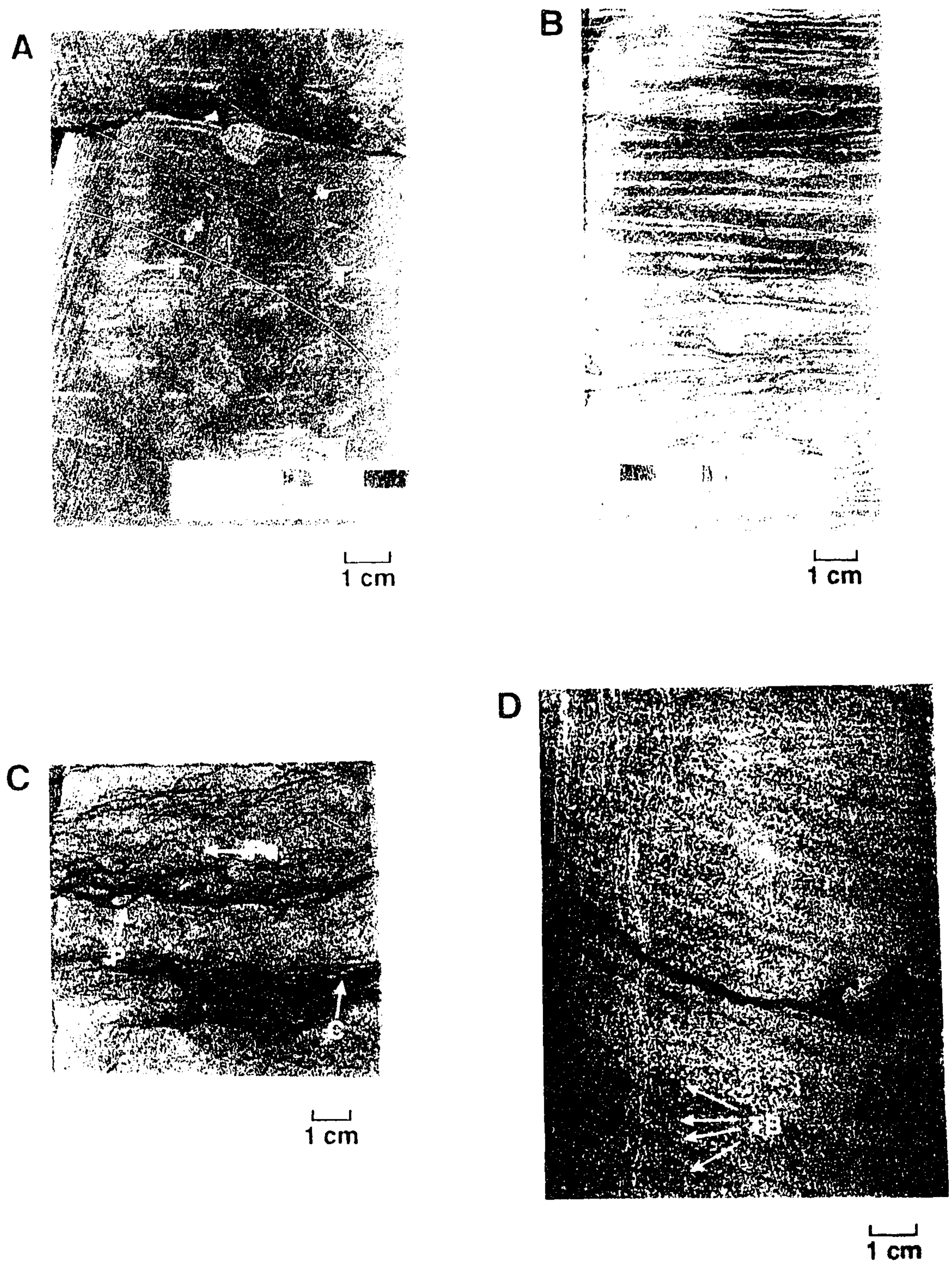
Plate 4.

A. Facies 1, massive sandy to silty mudstone with sharp-based laminae disrupted by *Teichichnus* burrows (T). Location: d-024-L/094-A-13, 1347.0m.

B. Facies 2A, interlaminated sandstones and mudstones with *Planolites* (P) and *Chondrites* (C) burrows. Location: a-005-L/094-A-13, 4406.5 ft.

C. Facies 2B, bioturbated, ripple laminated sandstones and mudstones with *Planolites* (P), *Chondrites* (C) and *Palaeophycus* (Pa). Location: d-059-L/094-A-13, 4222.5 ft.

D. Facies 3A, cross-stratified sandstone with abundant tidal couplets (TB). Location: d-003-L/094-A-13, 1323.7 m. Bar scale is 1 cm.


A
1 cm
B
1 cm
C
1 cm
D
1 cm

Stratification is characterized by parallel to horizontally laminated and normally graded, sharp-based sandstone beds (0.5 to 5 cm), with minor dispersed chert pebbles (< 5%) (Plate 5B). Some laminae and beds are separated by low angle, sharp to erosional (scoured) bounding surfaces that dip gently at 2 to 5 degrees. Burrow traces (up to 30%) consist of *Palaeophycus* and *Ophiomorpha* and are distributed throughout this facies. In addition, abundant post-depositional vertical fractures and styolites disrupt primary sedimentary and biogenic structures. Carbonaceous laminae and rip-up clasts (<2%) are distributed throughout the facies. Glauconite occurs throughout this facies as subrounded grains in abundances of < 1%. Cements (1-3%) consist of quartz overgrowth and pore filling siderite.

INTERPRETATION: Parallel- to horizontal-laminated, well sorted sandstones infer deposition by high velocity currents, reflecting a depositional product involving unidirectional flow within the lower part of the upper flow regime (Allen, 1993). The presence of burrows with pelleted and lined walls suggests an ecologically stressfull setting. *Palaeophycus* and *Ophiomorpha* are characteristic trace fossils of the *Skolithos* ichnofacies and are associated with shifting substrates in lower littoral to infralittoral, moderate to high energy environments, with abundant suspended food particles in the water column (Pemberton *et al.,* 1992). Due to the high current velocities associated with the deposition of this facies, little food will be deposited. Therefore, the predominant vertical burrows in this facies will be occupied by suspension feeders and passive carnivores. This facies is interpreted as having been deposited in an estuarine shoal environment of deposition.

4.2.7. FACIES 3D — MASSIVE AND DEFORMED SANDSTONES AND PEBBLY SANDSTONES

DESCRIPTION: Facies 3D consists of massive, unstratified, homogeneous and deformed, light to medium grey, fine to granular quartz sublitharenites, litharenites and pebbly litharenites up to [illegible].0 m thick. In some places, the existence of crude bedding can be inferred by the preferential orientation of mudstone and carbonaceous rip-up clasts, siderite clasts, and mudstone partings (Plate 5C). Soft sediment deformation features consist of common loading structures. Discrete, fine-grained glauconite is dispersed throughout the facies (1-2%). Cements consist of quartz overgrowths and siderite (1-4%). The massive, homogeneous appearance of this facies makes it difficult to discern the degree of bioturbation or confirm the presence of biogenic structures. However, rare *Palaeophycus* burrows have been observed within the deformed pebbly sandstones beds. In fining-upward sequences this facies commonly overlies a fluvial conglomerate facies.

INTERPRETATION: Massive bedding can be interpreted as the result of a very rapid deposition of sediment and/or rapid dewatering during compaction. The presence of load casts infers rapid sediment loading onto a hydroplastic surface. Siderite and carbonaceous mudstone and coal intraclasts are products of scour and rapid deposition by strong current velocities and suggest local substrate erosion and transport over relatively short distances. The recognition of marine trace fossils infers a marine rather than fluvial setting for this facies. Where this facies lies at the base of a fining-upward sequence and no marine trace fossil are present, it is interpreted as having been deposited in a channel environment. Where this facies is associated at the base of a coarsening upward sequence, and interstratified with Facies 3E, it is interpreted as having been deposited within a subtidal estuarine shoal/ sand flat environment.

4.2.8. Facies 3E — BIOTURBATED, FINE-GRAINED, MUDDY SANDSTONE

DESCRIPTION: Facies 3E (Plate 5D) consists of fine-grained, light grey, bioturbated (60 to 90%) muddy sandstone, tens of centimetres thick. The percentage of mudstone ranges between 20 to 40%. Stratification is absent due to intense bioturbation which has produced a massive to mottled appearance. Two distinct trace fossil suites are characterized by a moderate diversity, relatively high density, assemblage of vertical and horizontal grazing, suspension, and deposit feeding burrows identified as either *Palaeophycus, Terebellina, Helminthopsis, Chondrites, Teichichnus* , and *Skolithos*, or *Palaeophycus* and *Skolithos*. Organic detritus and glauconite are common throughout the facies.

INTERPRETATION: This facies typically overlies coarser grained facies and suggests decreasing flow strength and/ or sedimentation rates, and deepening of the water column. Mudstone laminae interbedded with muddy sandstones infers a mix of low velocity current transport and suspension sedimentation. The distinction between wave and tidal deposition of this facies is made difficult due to the intense bioturbation.

This facies is characterized by biogenic structures representing the *Cruziana* ichnofacies, and is interpreted as having been deposited under decreasing wave intensity. Environmental conditions typically range from medium to low-energy levels; with high concentrations of suspended and deposited food. Suspected trace makers are interpreted to include suspension and deposit-feeders as well as mobile carnivores and scavengers. Intense bioturbation by the resident infauna has completely reworked the sediment, destroying any primary sedimentary structures. As a result of reduced energy levels, ecologic stresses are minimal (Ekdale *et al.*, 1984); therefore, biogenic structures are dominantly horizontal, with less abundant vertical structures present. The presence of *Skolithos* and *Palaeophycus* overprinting the quiet water assemblage suggests the periodic establishment of higher energy levels, and turbid waters. Facies 3E is interpreted as either a low energy offshore marine or estuarine channel environment of deposition depending on its stratigraphic position within fining- or coarsening-upwards (channel vs. shoreface) facies associations.

4.2.9. FACIES 3F — CROSS-STRATIFIED, SANDSTONES, GRANULAR SANDSTONES AND PEBBLY SANDSTONES

DESCRIPTION: Facies 3F consists of fine- to very coarse-grained sublitharenite and litharenite sandstone with rounded to well rounded, poorly to moderately sorted chert pebbles dispersed throughout. This facies is characterized by low- to high-angle trough cross-bedding and horizontal laminations (Plate 6A). Imbrication of lithic and rip-up clasts along scour contacts is common. Cross-stratified beds display a crude normal grading. This facies is poorly sorted and interbedded with matrix-supported conglomerates of Facies 4B.2. Disseminated organic detritus gives a dark grey colouration to this facies.

INTERPRETATION: The cross-stratified pebbly sandstones are a product of lower flow regime bedload deposition of 2D and 3D dunes produced under unidirectional current flow. The absence of marine trace fossils and other marine indicators (i.e. glauconite) infers deposition within a fluvial environment. The bedding features observed in this facies are similar to those commonly observed in modern fluvial channel environments (Miall, 1992).

4.2.10. FACIES 4A—CROSS-STRATIFIED, CLAST-SUPPORTED CONGLOMERATE

DESCRIPTION: Facies 4A (Plate 6B) consists of normally graded, massive to crudely stratified chert pebble (2-32 mm) sublitharenite and litharenite conglomerate and low- to high-angle cross-stratified, well-rounded, chert pebble (2-16 mm) sublitharenite and litharenite conglomerate in bedsets up to 15 m thick. Basal bed and bedset contacts are sharp or erosive, with reliefs of 0.5 to 3.0 cm. This facies is characterized by a fining-upward trend in grain size. Sideritized mudstone rip-up clasts and coal intraclasts are common in horizontally stratified bedsets, giving rise to polymictic and polymodal textures. Unimodal and bimodal clast-supported conglomerates are thin and relatively rare. Clast imbrication is similarly rare. Matrix, as fine- to medium-grain sand and granules in this facies, may make up 30% of the rock by volume. Framework grains are fused by quartz overgrowth, megaquartz, chalcedonic quartz and rare siderite cement (1-5%). Clast-supported open framework conglomerates occur primarily at the base of Facies 4A and grade upwards into fine- to medium-grained matrix- and clast-supported, closed framework conglomerates.

INTERPRETATION: This facies contains massive to horizontal stratification and large-scale trough and planar tabular cross-bedding indicative of deposition from unidirectional bedload tractional currents. Massive bedding is interpreted to result from very rapid sediment deposition. Crude bedding commonly occurs in the lower parts of a bed, essentially showing the same fabric as a massive bedded section. Horizontal stratification is interpreted as the plane bed phase of upper flow regime transport.

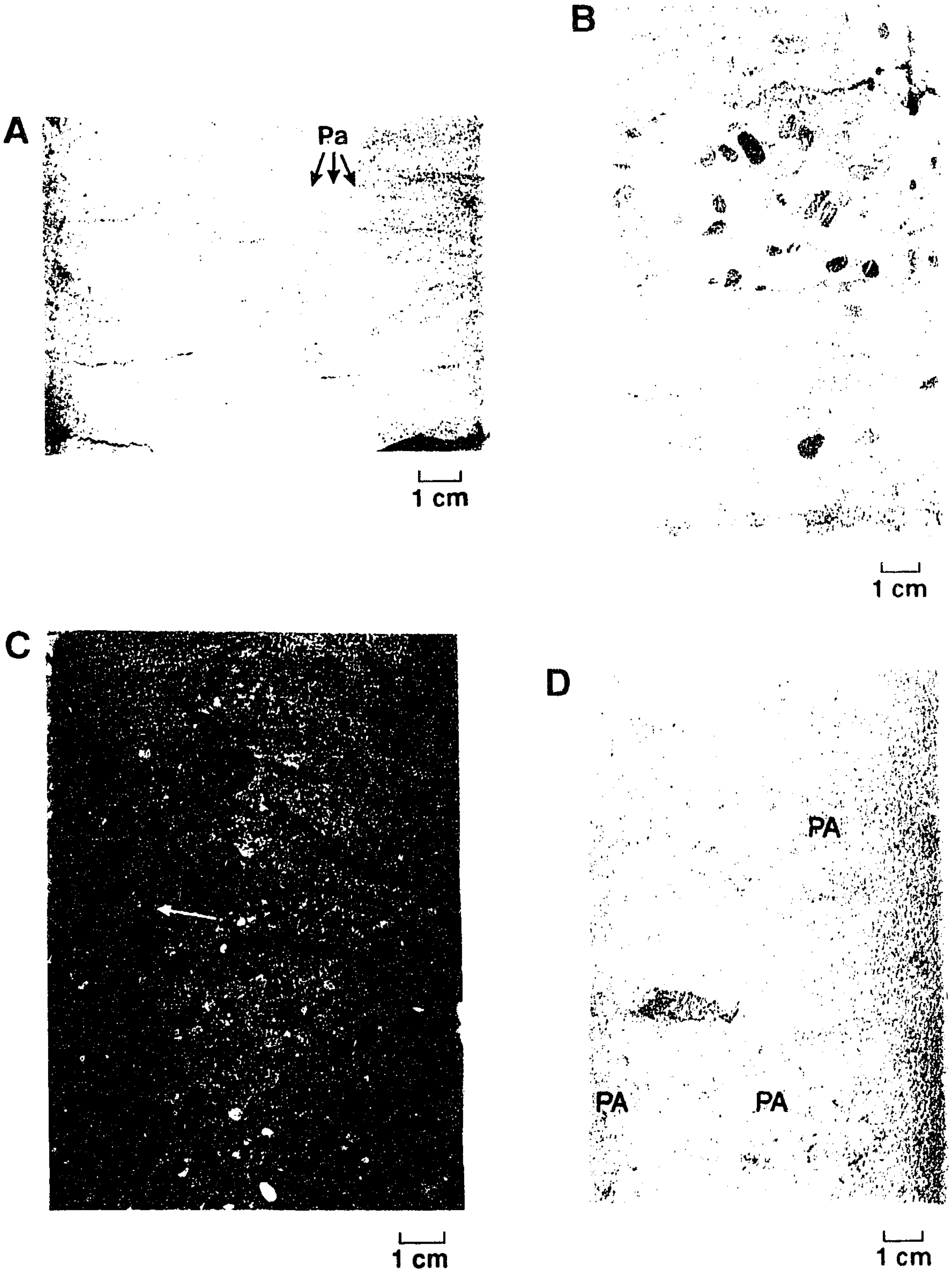
Plate 5.

A. Facies 3B, ripple laminated sandstone with *Palaeophycus* burrows (Pa). Location: b-054-L/094-A-13, 1344.0 m.

B. Facies 3C, parallel laminated sandstone with chert pebbles along bedding planes. Location: d-059-L/094-A-13, 4228 ft.

C. Facies 3D, massive and deformed sandstone and pebbly sandstone illustrating fluidization of gravel due to rapid and/ or differential sedimentation or slumping (arrow). Location: d-043-L/094-A-13, 4382 ft.

D. Facies 3E, bioturbated, fine-grained muddy sandstone with *Palaeophycus* (Pa) burrows. Location: d-059-L/094-A-13, 4241 ft.


A
Pa
1 cm
B
1 cm
C
1 cm
D
PA
PA
PA
1 cm

Sections of trough and planar tabular cross-bedding overly horizontal stratified units, inferring waning current strength within 2D and 3D dune phases of iower flow regime transport.

Normal grading within beds implies sorting of clast sizes and diminishing current flow strength during deposition (Klien, 1975; Harms *et al.*, 1982). This suggests that individual clast sizes were free moving relative to one another in the transporting . This feature is illustrated in cross-beds where the grain size and clast-sorting at of the bed is polymodal and contains the coarsest grain-size, transitionally overlain by a sorting inversion and grain-size decrease to bimodal clast-supported conglomerate, and capped by thin beds of unimodal, clast-supported granular conglomerate, with or without an open framework.

Deposition of clast-supported, open framework conglomerate requires that current velocities were strong enough so that the finer-grained material remained in suspension during transport and deposition of the coarser grained fraction. Thus there is an implied entrainment of loose sand during transport of the mature gravel (Steel and Thompson, 1983). Conglomerates interbedded with very coarse-grained sandstones, with sharp and/or scoured lower and gradational upper bounding surfaces, suggest separate events rather than a series of continous and fluctuating processes. The lack of a well developed clast imbrication suggests that transport and deposition processes restricted clast movement relative to adjacent clasts. Only in rare instances does clast imbrication occur, infering that individual clasts were able to move freely with respect to adjacent clasts and have assumed the orientation imposed by the flow mechanism (Harms *et al.*, 1982). This facies is interpreted as a fluvial channel fill.

4.2.11. FACIES 4B—MATRIX-SUPPORTED CONGLOMERATE

Subfacies 4B.1: Massive to Crudely Stratified, Matrix-Supported Conglomerates:

DESCRIPTION: Subfacies 4B.1 (Plate 6C) consists of texturally and mineralogically immature matrix-supported pebble (2.0 to >32.0 mm) litharenite conglomerate. Basal bedding contacts are consistently erosional and burrowing is limited to the basal contact of the facies. The burrows have tentatively been identified as *Arenicolites* and *Thalassinoides*, and are characterized by sharp-walled, unlined, "U" shaped or network forms that extend downward into the underlying argillaceous sediments. The sand matrix is fine- to very fine-grained and ranges between 35 and 45% of the rock by volume; however, this facies may also contain a carbonaceous mudstone matrix representing 45 to 60% of the rock volume. Angular siderite and pyritized mudstone rip-up and coal intraclasts are common, resulting in a polymictic and polymodal texture. Glauconite grains may be present. Framework grains are fused by authigenic quartz overgrowths, megaquartz, chalcedonic quartz and rare siderite and authigenic pyrite cements. Pebbles are randomly distributed within the matrix, displaying horizontal to sub-vertical orientations of the *A*-axis. Basal sections of this subfacies may show a thin veneer of vague clast imbrication. Massive-appearing beds range from 10 to 40 cm in thickness. Crude, horizontal stratification occurs within beds that are generally tens of centimetres thick. This unit immediately overlies either a sequence boundary (SB) or a ravinement surface (TSE).

INTERPRETATION: The presence of high amounts of intraformational-derived clasts relative to chert pebbles suggests a genetic affinity between substrate erosion and deposition of this facies. There appears to be two origins to the matrix-supported conglomerates: a) a channel lag, and b) a transgressive lag. The polymodal and polymictic texture suggests that particles were locally derived and transported short distances, with minimal reworking by currents before deposition. The lag is thin, obtaining a thickness of up to 20 cm. Thin, massive bedded, matrix-supported polymodal conglomerates suggest processes involving very rapid depositon. The absence of soft sediment deformation features (i.e. dish and flame structures) implies that dewatering of the sediment during compaction is not an important process in the formation of massive bedding within this setting. Similarly, the absence of biogenic structures suggests that burrowing was not a factor in the generation of this facies. The stratigraphic position of this subfacies suggests deposition as a lag at the base of a fluvial channel involving upper flow regime transport and unidirectional flow.

Where Subfacies 4B.1 overlies a burrowed contact, a marine rather than fluvial setting is inferred within the incised valley. Biogenic structures present at the base of this facies comprise an omission suite of trace fossil associated with firm grounds characteristic of the *Glossifungites* ichnofacies. The predominance of oblique burrow traces relative to bedding reflects the simplest means for an animal to excavate a burrow in a firm substrate. There is no indication of a pelleted or reinforced wall to the burrow structures incised into silty mudstones and muddy sandstones. This suggests that the substrate must have been fairly cohesive at the time of burrowing. The firm, dewatered substrate permits dwelling structures to remain open after the resident organisms abandoned them; subsequently becoming passively infilled during depositon of the overlying sediment layer.

MacEachern *et al.* (1992) suggest that the *Glossifungites* ichnofacies within terrestrial incised valleys may occur only at the seaward margin of the valley under estuarine conditions. The lowstand incision event creates widespread firmground conditions that are subsequently modified during transgression. Such modifications tend to remove evidence of lowstand deposition and re-exhume the substrate, thus favouring colonization by marine animals (MacEachern *et al.*, 1992). Within this setting, Subfacies 4B.1 represents deposition as a lag associated with surf winnowing from shoaling waves during shoreface erosion and landward translation during transgression.

During a relative rise in sea-level, high energy nearshore currents and storms will effectively transport material from the shoreface and redistribute the sediment seaward and landward. Swift (1968) suggests that shoreface ravinement surfaces are cut mainly by surf action along a narrow zone at the foot of the shoreface, therefore providing a mechanism for the emplacement of the *Glossifungites* ichnofacies.

Seaward, a lag may be deposited on the shelf in the lower shoreface to offshore transition zone. In this case, Subfacies 4B.1 is interpreted to result from the last storm events (Burgeois and Leithold, 1984) which reworked the shelf deposits prior to the maximum flooding and emplacement of open shelf mudstones. From figure 17, the current velocities inferred for movement of grain sizes greater than 2 mm is in excess of 45 cm/sec. Materials too coarse to be transported under such current velocities, are concentrated on the wave or tidal ravinement surface. The absence of stratification suggests that the finer grained sediment component was deposited very rapidly from suspension of waning currents rather than as bedload. With continued deepening of the overlying water column, the shoreface continues to retreat. Through deepening, the effect of wave transport of sediments diminishes, and can no longer modify the texture of the sediment. The transition from a sandstone matrix to mudstone matrix suggests a waning of flow strength near the sediment-water interface and deepening of the water column (MacEachern *et al.*, 1992).

Subfacies 4B.2: Cross-Stratified, Matrix-Supported Conglomerate:

DESCRIPTION: Subfacies 4B.2 consists of low-angle, cross-stratified, matrix-supported chert litharenite and sublitharenite pebble (2.0 to 16.0 mm clast size) conglomerate that is finer grained than Subfacies 4B.1 (Plate 6D). This facies is commonly interbedded with Facies 4A or gradationally overlies Subfacies 4B.1. Basal contacts are sharp or gradational. Siderite mudstone rip-up and coal intraclasts are common along the lower portions of sharp-based, low-angle foresets. Framework grains are fused by quartz overgrowth, chalcedonic quartz, megaquartz and rare siderite cements. The matrix component of this facies can represent up to 50% of the rock by volume, consisting of fine- to medium-grained litharenite sandstone. Glauconitic content ranges between 0 and 4%, with the glauconite occurring as discrete, bright green, sub-angular to sub-rounded grains. Cross-beds have sharp bases and are overlain by polymodal, closed-framework, matrix-supported conglomerate. Interstitial sand is fine- to very coarse-grained, becoming finer-grained upwards within individual bedsets. Polymodal, clast-supported conglomerate grades upwards to bimodal, clast-supported, closed-framework conglomerate. Beds are normal-graded, with clast imbrication being rare or absent. Low-angle foresets are parallel and are characterized by angles of 7 degrees or less. Beds are between 5.0 and 12.0 cm thick, with bedset thicknesses of up to 0.8 m.

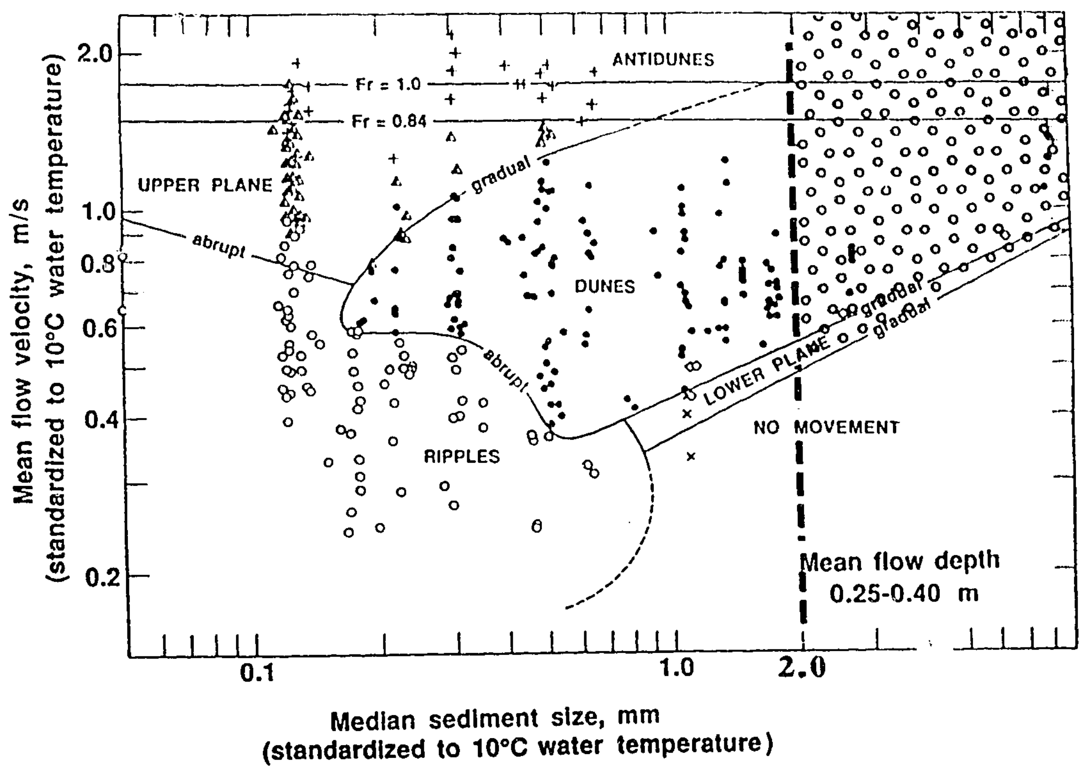


Figure 17. Plot of mean flow velocity against median sediment size showing stability fields of bed phases (modified from Ashley, 1993). Pattern block shows the stability field in terms of flow velocities and clast sizes greater than 2 mm for sedimentary structures in subfacies 4B.1 - channel lag and transgressive lag conglomerates.

INTERPRETATION: The lateral continuity of Subfacies 4B.2 suggests that depositional processes responsible for the origin of facies 4B.2 occurred over a wide geographic extent. Clifton (1981) interpreted pebbly sandstone cross-beds in the Miocene Cedienta Range to be the product of high amplitude waves with periods between 8 and 12 seconds. Bourgeois and Leithold (1984) also conclude that reworked conglomerates in sandstones beds at Floras Lake, S.W. Oregon are the product of long period swells forming low amplitude, low-angle cross-bedded, migrating nearshore bars. Nemec and Steel (1984) suggest that in wave-dominated settings, conglomerates in the lower shoreface reflect mainly onshore transport and consist of lenticular, sheet-like units which may be either lag deposits or dominated by low angle cross-stratification. They infer that the latter case is produced by the shoreward movement of low bars or megaripples, becoming sandy in the upper half of individual units (i.e. only the lower portions of the foresets are conglomeratic).

Low-angle cross-bedded units within the lower Cretaceous Moosebar-Gates Formations may have been similarily interpreted to result from long period oscillatory waves in the shoreface or to depths below fair weather wave base (Leckie and Walker, 1983).

Leckie (1988) interprets that coarse grained ripples, with wavelengths on the order of 2 to 5 m are common features on transgressive surfaces associated with upper and lower shoreface sediments and finer-grained sediments within offshore-transitional environments. In these environments, coarse-grained ripples are interpreted to form by oscillartory currents in depths that range from 3 to 160 m. Leckie (1988) also implies that two-dimensional coarse-grained ripples are formed, when the sediment is medium to very coarse-grained sand, as the product of oscillatory or oscillatory-dominated flow.

The gradational transition upward from subfacies 4B.1 to subfacies 4B.2 is similar to lag deposits, reflecting onshore transport, which are sometimes molded into megaripple forms as a result of oscillatory current reworking (Nemec and Steel, 1984). Subfacies 4B.2 may have formed by similar processes during moderate to high energy and/or long period oscillating wave currents following the emplacement of subfacies 4B.1. Low-angle cross-beds may be the product of large, low amplitude migrating bedforms. Subfacies 4B.2 is interpreted as being deposited in a lower shoreface environment.

Subfacies 4B.2 can also be transitionally overlain by Facies 3G. In such cases the facies exhibits a sharp or scoured base with a lining of intraformational rip-up clasts that grade upwards into medium- to very coarse-grained sandstone or pebbly sandstone. In such instances, subfacies 4B.2 is not laterally extensive, and the boundaries between subfacies 4B.2 and 3G may be gradational. Subfacies 4B.2 interbedded with facies 3A and/or 3G is interpreted to represent large scale trough cross-bedding and low and high angle planar tabular cross-bedding formed under lower flow regime conditions. Where it is interbedded with Facies 4A and/or 3G, subfacies 4B.2 is interpreted as lateral accretion bedding associated with laterally migrating bedforms during abandonment of the fluvial channel system (Rust, 1978; Nemec and Steel, 1984).

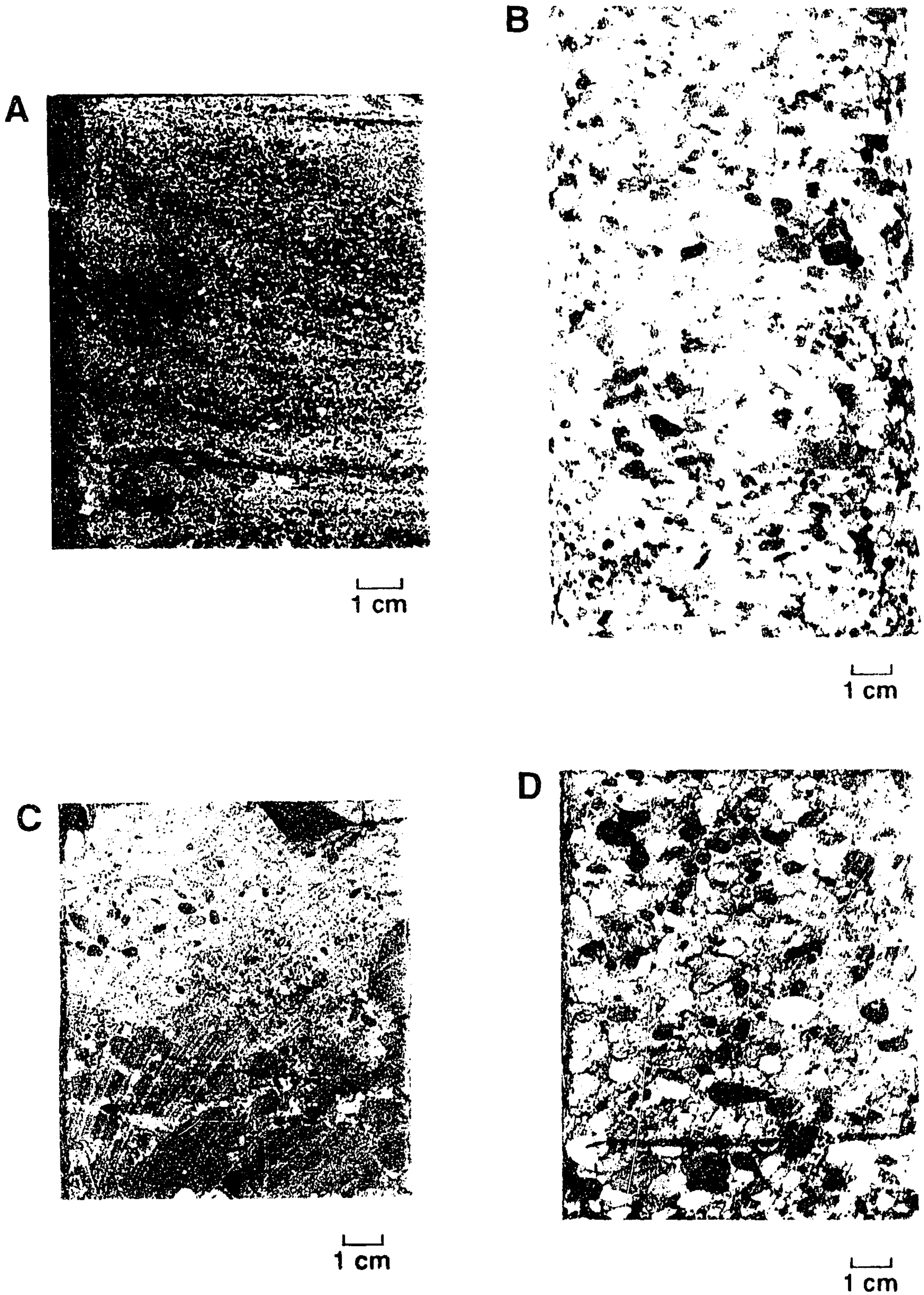
Plate 6.

A. Facies 3F, cross-stratified, very coarse-grained sandstone/granular sandstone and pebbly sandstone illustrating tangential laminations interpreted as trough cross-bedding. Location: d-047-L/094-A-13, 4206 ft.

B. Facies 4A, clast-supported conglomerate, showing moderate to high angle beds, normal grading and increase in sorting from polymodal to bimodal distributions upwards within beds, interpreted as large scale trough cross-bedding.
Location: d-057-L/ 094-A-13, 4237 ft.

C. Facies 4B.1, massive to crudely stratified, matrix-supported, polymictic and polymodal conglomerate with abundant intraformationally derived sideritized mudstone clasts in beds illustrating normal grading. Location: d-059-L/094-A-13, 4241.3 ft.

D. Facies 4B.2, cross-stratified, matrix-supported conglomerate with polymodal clast distribution, illustrating low angle bedding and normal grading of clasts.
Location: d-057-L/094-A-13, 4304 ft. Bar scale is 1 cm.


A
1 cm
B
1 cm
C
1 cm
D
1 cm

4.2.12. FACIES 5 — COAL AND CARBONACEOUS MUDSTONES

Subfacies 5A:. Coal and Argillaceous Coal.

DESCRIPTION: This facies consists of coal beds or argilaceous coal horizons. Coals are bright with dull bands, 5 to 20 centimeters thick, sharp-planar based, with/ without rootlets extending downward into underlying carbonaceous mudstones or interbedded mudstones, siltstones and very fine grained sandstones. Argillaceous content ranges between 10 - 50%; mainly clay-size grains interbedded with coal laminations. Coals are highly friable, with poor to very poorly develop . cleavage. However, because coals are thin and laterally discontinuous they possess no real commercial value.

INTERPRETATION: Coal and argillaceous coal beds and laminations are interpreted to have been deposited within low oxygenated, chemically reducing, brackish to freshwater environment, with abundant vegetation. This facies is interpreted as a poorly drained swamp or salt marsh environment similar to those on the U.S. east coast (Frey and Howard, 1986).

Subfacies 5B: Black Carbonaceous mudstones.

DESCRIPTION: Black carbonaceous mudstones and shales have clay sized grains < 4 microns (< 8 Ø) with a very high carbonaceous component estimated between 35 to 40% giving the distinctive dark grey-black coloration to this unit. Finely disseminated pyrite crystals and pyrite nodules are common, with rare occurences of Limonite-Goethite observed locally. Basal contacts are erosional, bioturbated, sharp-planar or gradational. In some units, 1 to 3 cm long coal spars are present along the basal contact. Carbonaceous mudstones beds are 0.2 to 20 cm thick, with mean thickness of

12 to 15 cm. Upper unit contacts are sharp, or rooted where overlain by coal beds. Carbonaceous mudstones display massive bedded intervals which are 10 to 18 cm thick. Biogenic structures are either absent or common. Where common, burrows appear to have a low ethologic and trophic diversity dominated by deposit-feeders. Trace fossils have been identified as *Planolites* . Rootlets are rare to common features within the unit.

INTERPRETATION: Carbonaceous mudstones are interpreted to form in a highly vegetated and essentially argillaceous brackish to fresh water environment as can be inferred from its stratigraphic position below subfacies 5A and above intertidal sediments. The deposits are associated with low oxygenated, chemically reducing environments, with abundant vegetation inferred from high concentrations of plant material (Facies 5A), common occurences of rootlets and pyrite, low diversity and density monospecific trace fossil assemblage and the massive appearance of the facies. This facies is interpreted as a poorly drained swamp or salt marsh environment similar to those on the U.S. east coast (Frey and Howard, 1986).

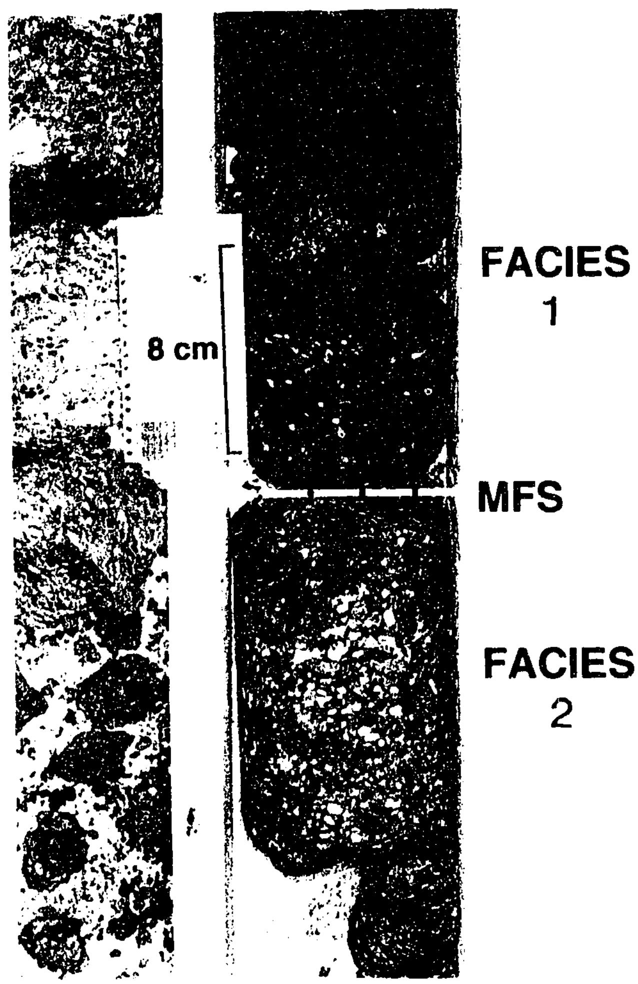
4.3.0. BUCKINGHORSE FORMATION SEDIMENTARY FACIES

Two facies of the Buckinghorse Formation are interpreted to be of lower shoreface to offshore origin. Both facies are part of the lithostratigraphic Buckinghorse Formation within the study. The interpretation of the various Buckinghorse Formation facies are similar to modern and ancient environments identified by Swift (1968), Clifton (1981), Bourgeois (1980), Bhattacharya and Walker (1991), and MacEachern et al (1992). The following facies are summarized in Table 6 and illustrated in plate 7.

Table 6. Summary of sedimentary characteristics within sedimentary facies, Buckinghorse Formation, Aitken Creek area, northeastern British Columbia.

Facies	Lithology	Thickness	Bedding Features	Physical Sedimentary Structures	Biogenic Sedimentary Structures	Sedimentary Processes	Depositional Environment
1	Shaley Mudstone	> 15 m	Dispersed chert pebbles (<10%) within bottom 10 cm above sharp contact with Facies B2; rare, sharp-based, normal graded siltstone laminations.	Massive appearing Rare parallel laminations	Rare *Planolites* & *Helminthopsis*	Minor bedload traction currents Predominantly suspension depostion below storm wave base	Offshore-Open Marine Shelf
2	Matrix-supported, chert pebble (2-32 mm) conglomerate	< 2 m	Sharp and erosional based; normal grading; Fine-grained sandstone matrix at base transitional to mudstone matrix, mudstone content increases upwards from 10% at base to 55-65% at the top of the facies; bed thickness 0.15-0.5 m; horizontal clast orientation.	Massive appearing	None	High energy, Upper to lower flow regime, oscillatory currents	Transgressive Lag

Plate 7. Photograph of matrix-supported conglomerate (Facies 2) overlain by massive shaley mudstones (Facies 1). The contact between these two facies is a marine flooding surface. Location: d-019-K/094-A-13; 4279'6"-4280'.


8 cm
FACIES
1
MFS
FACIES
2

5.0.0. FACIES ASSOCIATIONS

The facies described in section 4.0.0. have been grouped into facies associations that represent a vertical succession of facies. Each association is bounded above and below by either sequence boundaries, transgressive surfaces of erosion or marine flooding surfaces. Two deltaic (Gething Formation), one fluvial (Bluesky Formation), three estuarine (Bluesky Formation), and two open marine (Bluesky and Buckinghorse Formations) facies associations have been interpreted within the Aitken Creek study area.

5.1.0. GETHING FORMATION FACIES ASSOCIATIONS.

Two distinct re-occuring delta plain facies associations have been identified in the upper Gething Formation. They follow three basic basal contact, well log, and grain-size trends: (1) erosionally based, coarsening upward; (2) erosional or sharply based, fining upward; and (3) erosional or sharply based, irregular or serrated. These trends, along with the accompanying core descriptions (Appendix A) have been used as the basis for the description, definition, and interpretation of the associations presented below.

5.1.1. INTERDISTRIBUTARY BAY-FILL FACIES ASSOCIATION

DESCRIPTION: The facies association ranges between 1.0 to greater than 10 m thick, uniformly distributed within the study area, and dominated by interbedded carbonaceous mudstone, siltstone and sandstone, which may be locally incised by fining upward channel fills (Distributary channel-fill facies association). The order of the vertical facies relationships is highly variable, but local fining- and coarsening upward trends are observed. In any given occurrence of this facies association, nonmarine facies usually become predominant within the upper one-fifth of the facies association. Interdistributary bay-fill deposits (Fig. 18) are distributed throughout the study area in a series of stacked parasequences separated, for the most part, by marine flooding surfaces, or truncated by a fourth order sequence boundary .

Plate 8 illustrates a typical cored interval of the interdistributary bay-fill facies association. Massive silty mudstones (Facies 1) increase in sand content upwards and contain resedimented plant detritus. Facies 1 contains sharp based sandstone beds, upto a few cm thick in its upper reaches, that passes upwards into interbedded sandstones, siltstones and mudstones (Facies 2), characterized by scoured or sharp based, current- and wave ripple laminated, parallel laminated and climbing ripple cross-laminated fine-grained sandstone (upto tens of cm thick). Mudstone content decreases upwards. Facies 1 and facies 2 can locally be pervasively bioturbated, and contains abundant synaeresis cracks, bedded and nodular siderite, and pyrite. Facies 2 may be locally incised by a 1.0 to 2.0 m thick fining upward sucession of trough cross-bedded to climbing ripple cross-laminated, medium- to fine-grained sandstone (Facies 3A and/ or Facies 3B) with abundant mudstone and coal intraclasts. This unit is transitional upward into either interbedded sandstone, siltstone and mudstone (Facies 2), which may become intensely rooted within the upper parts of the facies, or carbonaceous mudstones and coals (Facies 5) which contain abundant *in situ* rootlets and/ or rhyzoliths, and pyrite.

Table 7. Table of lithology, sedimentary structures and ichnology symbols used in facies association figures.

LITHOLOGY

- Sandstone
- Silty Mudstone
- Clast-Supported Conglomerate
- Argillaceous Coal / Carbonaceous Mudstone
- Mudstone
- Matrix-Supported Conglomerate
- Coal
- Sandy Mudstone

SEDIMENTARY STRUCTURES/CONTACTS

- Parallel Stratification
- Low Angle Cross-Stratification
- High Angle Cross-Stratification
- Trough Cross-Stratification
- Ripple Stratification (current)
- Ripple Stratification (wave)
- Wavy Bedding
- Lenticular Bedding
- Flaser Bedding
- Imbrication
- Normal Graded Bedding
- Erosive Bedding Contact
- Internal Erosive Contact
- Sharp Bedding Contact
- [illegible]
- Micro Faults

ICHNOFAUNA

Ar	*Arenicolites*	Sk	*Skolithos*
Ch	*Chondrites*	Tei	*Teichichnus*
Pa	*Palaeophycus*	Th	*Thalassinoides*
Pl	*Planolites*	Ast	*Asterosoma*
Op	*Ophiomorpha*		

SEQUENCE STRATIGRAPHIC SURFACES

SB – Sequence Boundary
ITS – Initial Transgressive Surface
TSE – Ravinement Surface
MFS – Marine Flooding Surface

ACCESSORIES COMPONENTS

- Mud rip-up Clast
- Coal Chips
- Wood Imprints
- Leaf Imprints
- Carbonaceous Laminae
- Chert Pebble
- **DST Interval**
- Perforated Interval
- Py Pyrite
- Sd Siderite
- G Glauconite

108

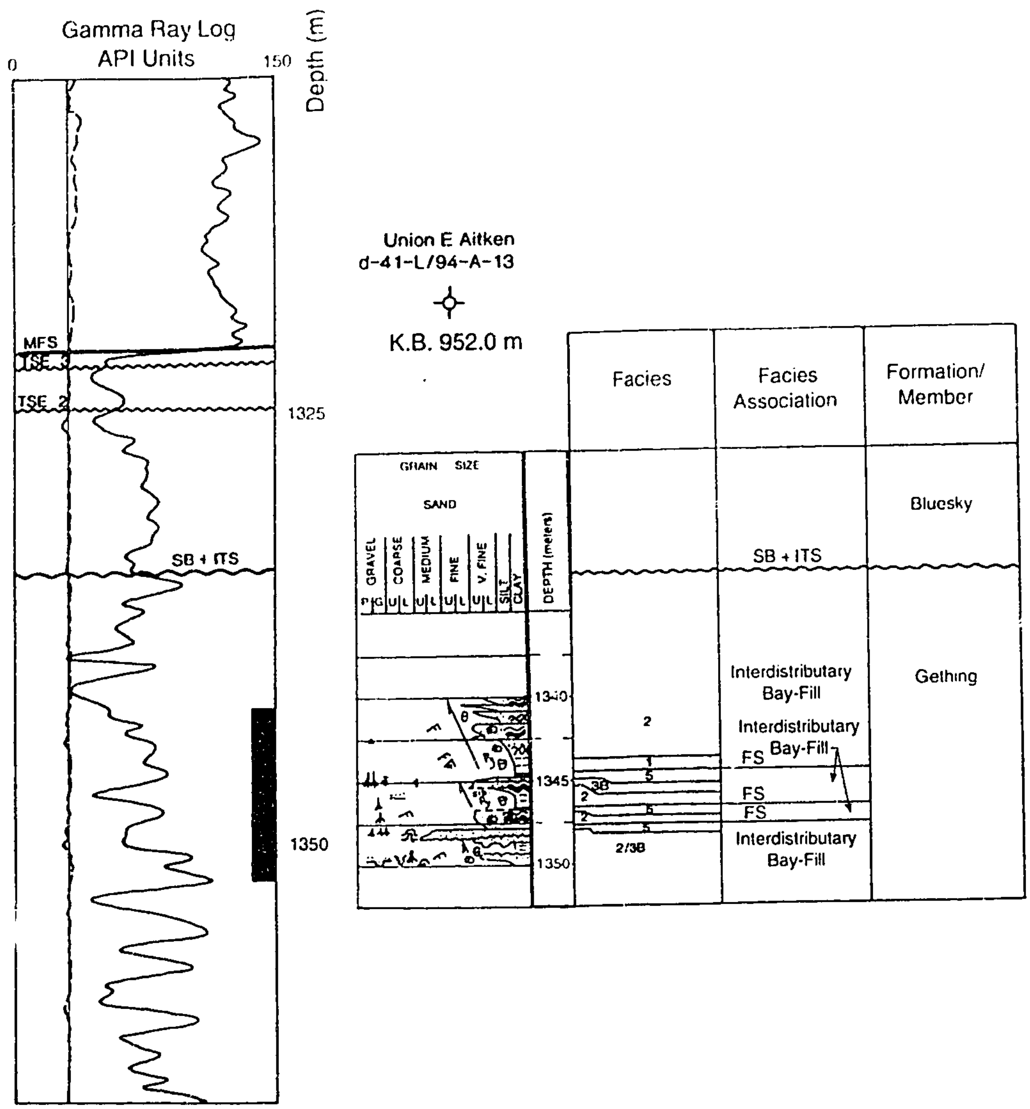
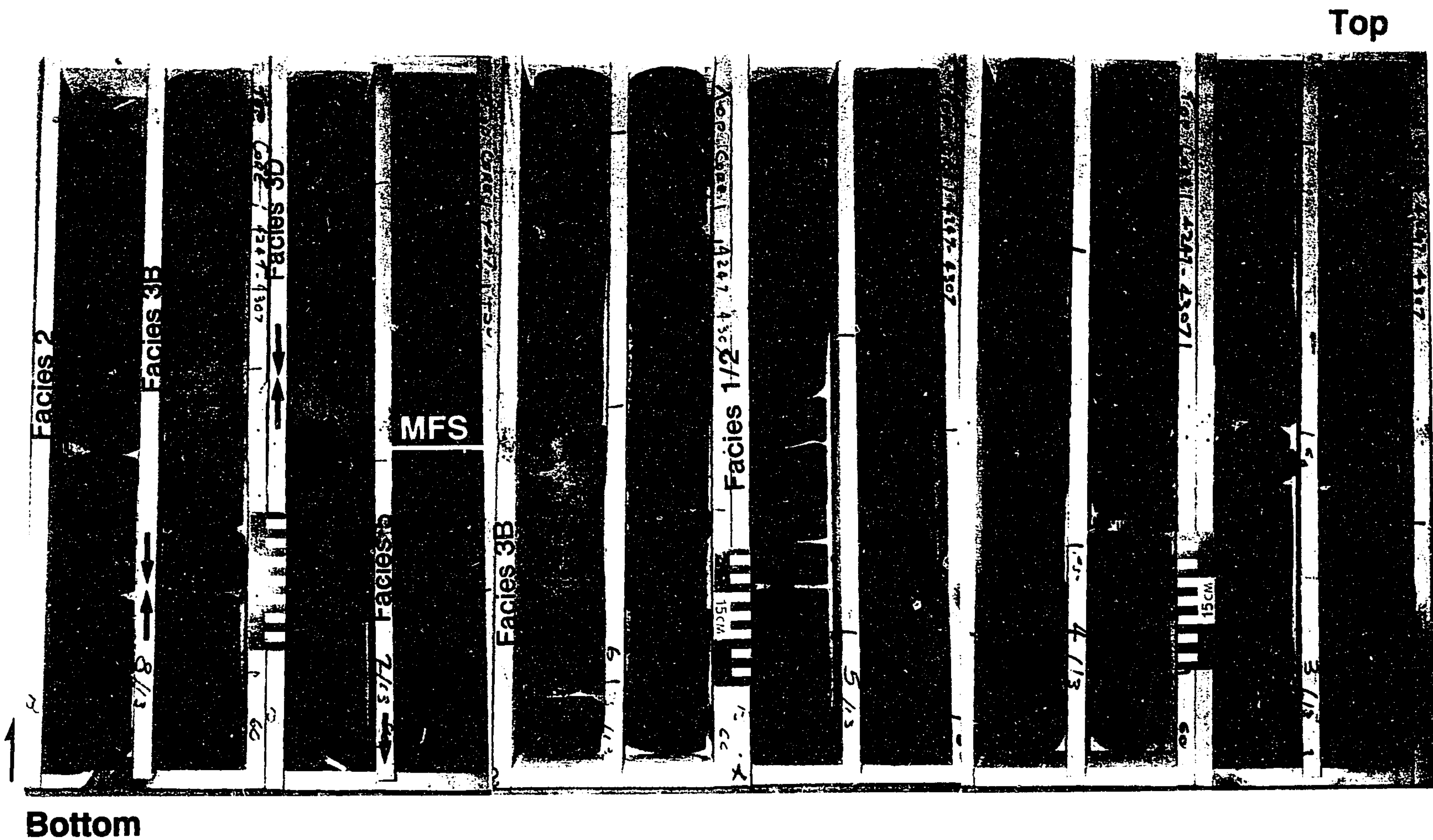


Figure 18. Interdistributary bay-fill facies association (see text for description and interpretation). Refer to Table 7 for key to lithology and symbols used in diagrams.

Plate 8. Whole core photograph of a Gething Formation interdistributary bay-fill facies association. A marine flooding surface (MFS) separates a coal bed (Facies 5) below from bay/ lagoon? sandstones and mudstones (Facies 2) above. Location: d-030-L/094-A-13.


Top
Bottom
Facies 2
Facies 3B
Facies 3D
MFS
Facies 3B
Facies 1/2
15CM

Palynomorphs analysed from the facies association are characterized by occasional to rare abundances, generally poorly preserved and corroded, with common occurrences of terrestrial palynomorphs and rare marine microplankton. Palynomorphs represented consist of common undifferentiated Spores and Palynomorphs, rare to very rare Dinoflagellates, Bisaccate pollen, *Cicatricosisporites* sp., *Aequitriradites* sp., *Contignisporites* sp., ? *Cribroperidinium* sp., *Cerebropollenites mesozoicus* , cf. *Spinidinium* sp, ? Fungal spore, ? Scolecodont, ? *Meiouroganyaulax* sp. The kerogen type is dominated by vitrinite (100%). Vitrinite is characterized by a mixture of normal size and very fine grained particles, which may be partly degraded, and/or partly to totally oxidized.

INTERPRETATION: This facies association was deposited within a moderate to low energy, shallow water, brackish to nonmarine environment with moderate oxidation and slight anoxia on the distal fringes of coastal plains. Similar depositional settings have been described by Elliott (1974; 1986). The basal silty mudstone facies is indicative of low current velocities involving predominantly suspension deposition. Low velocity currents are inferred from the intense bioturbate nature to some intervals, suggesting low sedimentation rates. The trace fossil assemblage and palynomorphs infer restricted, shallow, subtidal conditions (Ekdale *et al.*, 1984; Wightman *et al.*, 1987; Beynon *et al.*, 1988; Pemberton and Wightman, 1992; J. Ford, pers. comm., 1994). Coarsening- and increasing sandstone content upwards characterizes Facies 2. Ripple cross-stratification and planar laminations in sandstones are interpreted as being deposited by traction currents during, higher energy, episodic events (i.e. storms or seasonal flood discharge), and mudstone interbeds reflect suspension deposition during slack water or fairweather conditions. The upper parts of some current rippled sandstone beds may be gradationally into wave ripples which suggests reworking of the upper part of the bed by wind generated, oscillatory currents (Elliot, 1986). The increased thickness and frequency of sandstone interbeds infers an overall increase in, but highly variable sedimentation rates. The low diversity and low density trace fossil assemblage and the abundant synaeresis cracks infer stressed ecological settings and fluctuating salinity, and are consistent with a shallow brackish water bay interpretation (Pemberton and Wightman, 1992).

Thicker sandstone beds may fill crevasse channels and splays. Fining-upward sandstones into Facies 2 are interpreted and crevasse channel deposits comparable to channels identified by Elliot (1974). Crevasse splay deposits displaying climbing ripples infer rapid deposition in sediment laden waters under lower flow regime conditions. Some splay sandstones display a transition from parallel laminated sandstones to asymmetrical ripple laminated sandstones, which may become capped by symmetrical ripples in the upper reaches of the splay or pervasively bioturbated and rooted. This indicates waning traction current energy or increase in flow depth whereby fine-grained sandstones are initially deposited as upper flow regime plane bed deposits gradational upwards in to lower flow regime current ripple bedding. The upper reaches of the splay may become reworked by waves, rooting, or by burrowing organisms Within crevasse splay sandstones, the lower unit is interpreted to occur within an brackish water environment. However, the upper sections of crevasse splay sandstone may become moderate to intensely rooted, or overlain by carbonaceous mudstones and coals which are intensely rooted, indicating suspension deposition of fine-grained material, shoaling upwards and establishment of freshwater conditions (Pemberton and Wightman, 1994).

The environments comprising the bay-fill facies association probably include interdistributary bays, lagoons, deltaic and fluvial floodplains (Elliot, 1974; 1986; Coleman and Prior, 1982; Bhattacharya and Walker, 1991). The top of the carbonaceous mudstone and coal deposits marks the top of a parasequence and is capped by a marine flooding surface which terminates plant growth and re-establishes marine bay conditions (Facies 1) within the delta plain (Pemberton and Wightman, 1994). The interdistributary bay-fill facies assoiciation may become laterally replaced by delta front or distributary channel and levee environments. By comparison, a similar modern interdistributary bay fill facies sucession has been documented by Coleman and Gagliano (1965) and Coleman and Prior (1982) from the Mississippi delta (U.S.A.).

5.1.2. WELL LOG CHARACTERISTICS:

Gething interdistributary bay-fill gamma ray log profiles have abrupt lower contacts, serrated, bell-, funnel- and linear shapes, and abrupt or gradual upper contacts (Fig. 18). Log profiles illustrate a high degree of heterogeneity, with serrated bell-shaped, sharp-based profiles, and increasing gamma ray intensity upwards. Gamma ray intensity of 20 to 30 API units is indicative of a relatively clean sandstone. Acoustic travel time values show abrupt increases which are interpreted as coal beds.

5.1.3. DISTRIBUTARY CHANNEL-FILL FACIES ASSOCIATION

DESCRIPTION: This facies association is characterized by an erosional basal contact, fining-upward in grain size, and thickness greater than 10 m. A typical core description and well log response are illustrated in figure 19. The erosional contact is overlain by lag of carbonaceous mudstone and coal intraclasts (Facies 4). This is followed by upto 1.0 m of medium grained, massive sandstone and/ or parallel bedded sandstones (Facies 3D & 3C). This is in turn overlain by trough cross-bedded fine-grained sandstones, tens of cm thick (Facies 3A). These sandy facies are replaced upwards by parallel to current ripple laminated fine-grained sandstones and intensely bioturbated muddy fine-grained sandstones (Facies 3B). This is overlain by interbedded fine-grained current ripple laminated sandtones and mudstones (Facies 2) grading upward into massive mudstones, with rare wave- and current ripple laminations (Facies 1). Facies 3A upward to Facies 1 may be weak to strongly rooted, and contain synaeresis cracks, bedded siderite, pyrite and resedimented plant material (up to 10%). Within the facies association, several fining-upward bed sets of cross-bedded to ripple laminated sandstones occur. Biogenic structures are rare and characterized by a low diversity and low density assemblage consisting of *Chondrites, Palaeophycus* and *Planolites.*

Palynomorphs analysed from the distributary channel-fill facies association have low abundances, generally poorly preserved, with rare occurences of marine/ brackish microplankton and terrestrial palynomorphs. Palynomorphs represented consist of rare undifferentiated Palynomorphs, and very rare Dinoflagellates, Bisaccate pollen, ? Ceratioid cyst, ? *Cribroperidinium* sp.,

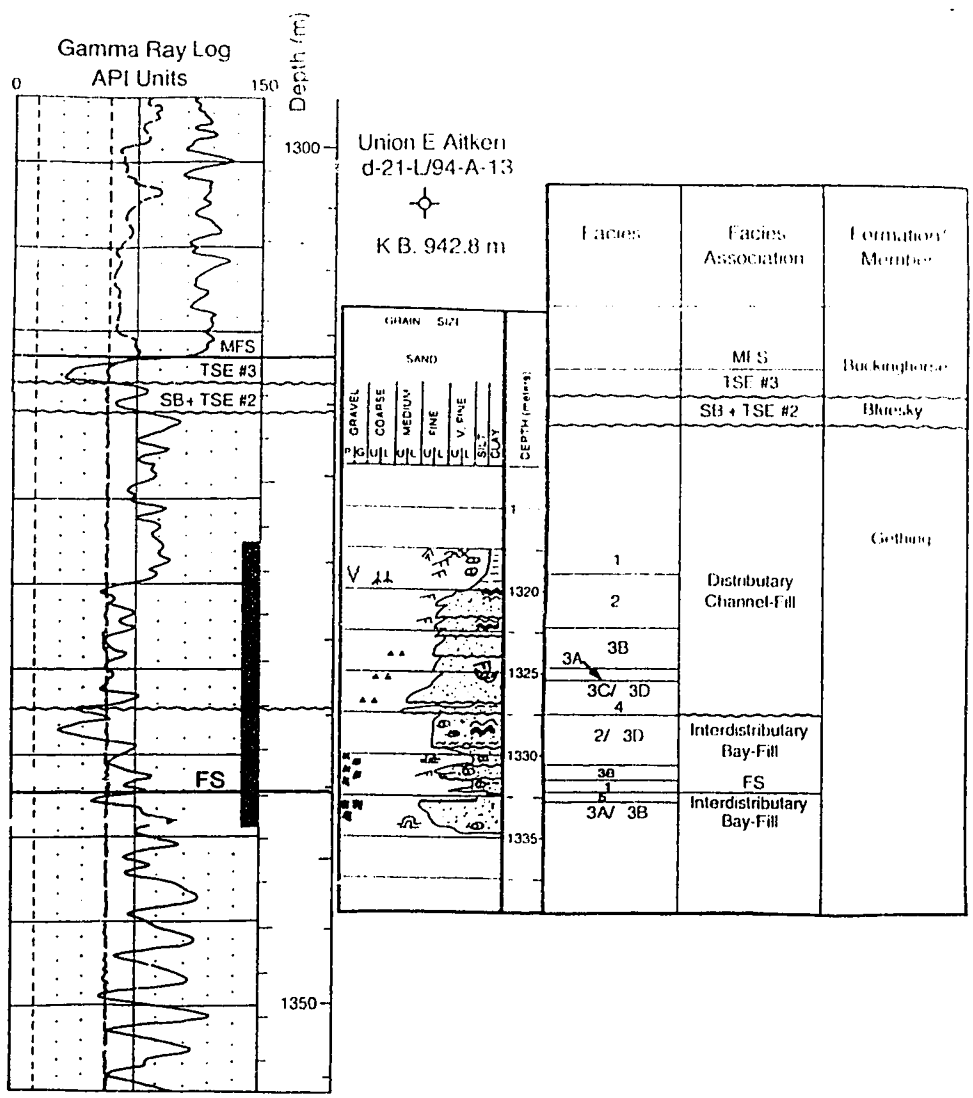


Figure 19. Distributary channel-fill facies association. Channel base represents local incision into interdistributary bay-fiii deposits. The channel is filled with predominantly muddy sandstone and capped by a transgressive surface of erosion (TSE). Refer to Table 7 for key to lithology and symbols used in diagrams.

Cicatricosisporites sp., *Alisporites grandis*, *Pilosisporites trichopapillosus*, and *Contignisporites* sp. The kerogen type is dominated by vitrinite (100%).

INTERPRETATION: This facies association is interpreted as a channel-fill based on the erosional lower contact, basal lag deposit and overall fining-upward trend in grain-size. The channel-fill facies association displays sedimentary features similar to features identified within modern and ancient distributary channels by Coleman and Gagliano (1965), Elliott (1974; 1975; 1986), Coleman and Prior (1982), Hopkins (1985), Moslow and Tillman (1986), and Bhattacharya and Walker (1991). A distributary channel rather than estuarine channel is favoured due to the absence of tidal bedding, bidirectional cross-stratification, reactivation surfaces, and most biogenic structures. Additionally, this facies association contains a high percentage of resedimented plant detritus than estuarine channel and point bar/ abandoned channel facies associations identified in section 5.3.7 and 5.3.9.

The presence of marine/ brackish microplankton and marine trace fossils suggests that the active channel was not fluvially dominated but probably resided in a marginal marine setting. Palynomorphs and trace fossil present infer deposition in an evironment with normal oxidation, slight winnowing and possible marine/brackish influence as would be expected within a distributary channel (J. Ford, pers. comm., 1994).

The floor of the distributary channel is characterized by massive and planar parallel bedding inferring upper flow regime conditions involving unidirectional currents, bottom scouring,and rapid bedload transport during flood conditions

(Moslow and Tillman, 1986). The overlying trough cross-bedding is interpreted as the active distributary channel and infers active sand transport and bed-form migration by lower flow regime currents. The normal graded bed sets within the overall fining-upward channel trend infer channel filling by a series of separate waning current events, perhaps associated with flood stages of the river. Abandonment of the channel is inferred from the overall fining-upward trend in the channel-fill sequence (Elliott, 1986). Abandoned channel deposits are characterized by predominantly suspension deposition periodically interrupted by higher energy events depositing current and wave ripple laminated sandstones and siltstones. The abundance of rootlets, siderite beds, pyrite and carbonaceous nature of the upper reaches of the abandoned channel suggest slight anoxia and reducing conditions within poorly drained swamps or marshes within a nonmarine setting. The distributary channel-fill facies association may become replaced laterally by levee or interdistributary bay environments, seaward by distributary mouth bar deposits, and landward by fluvial dominated distributary channel deposits (Elliott, 1974; 1976).

5.2.0. BLUESKY FORMATION FLUVIAL FACIES ASSOCIATION

A distinct reoccurring fluvial facies association has been identified in the Bluesky Formation. The association is bounded below by a sequence boundary, and above by the initial transgressive surface produced during sea-level rise and back-filling of the incised valley with estuarine sediments. It conforms to two basic basal contact, well log, and grain-size trends: (1) erosional or sharply based, fining upward; and (2) erosional or sharply based, cylindrical and/or serrated. These trends, along with the accompanying core descriptions (Appendix A) have been used as the basis for the description, definition, and interpretation of the association presented below.

5.2.1. Fluvial Channel-Fill Facies Association

Description: This facies association is underlain by a sequence boundary and illustrates an upward fining trend (Fig. 20A). The facies association is commonly found within conglomeratic bodies that map as isolated, discontinuous pods or bars and is up to 22 m thick. The lower erosional contact is commonly overlain by a lag (Facies 4B.1) of interformationally derived material up to 30 cm thick. This in turn is overlain by several metres of large-scale, low- to high angle trough, plane-parallel, and planar tabular cross-stratified conglomerates (Facies 4A and 4B.2) and pebbly sandstones (Plate 9) (Facies 3G). Any one succession can contain several normally graded, fining-upward beds of massive to variably cross-stratified conglomerate separated by internal scour surfaces floored by basal intraclast lags. This facies association is capped by a marine flooding surface representing the initial onset of transgression above the lowstand incised valley- fill deposits.

Interpretation: This facies association is interpreted as a fluvial channel-fill. This is suggested by: a) the overall fining-upward trend; b) conglomeratic lithology with basal and internal erosional surfaces; and c) an isolated, discontinuous geometry (Fig. 20). Conglomerate textures are predominantly

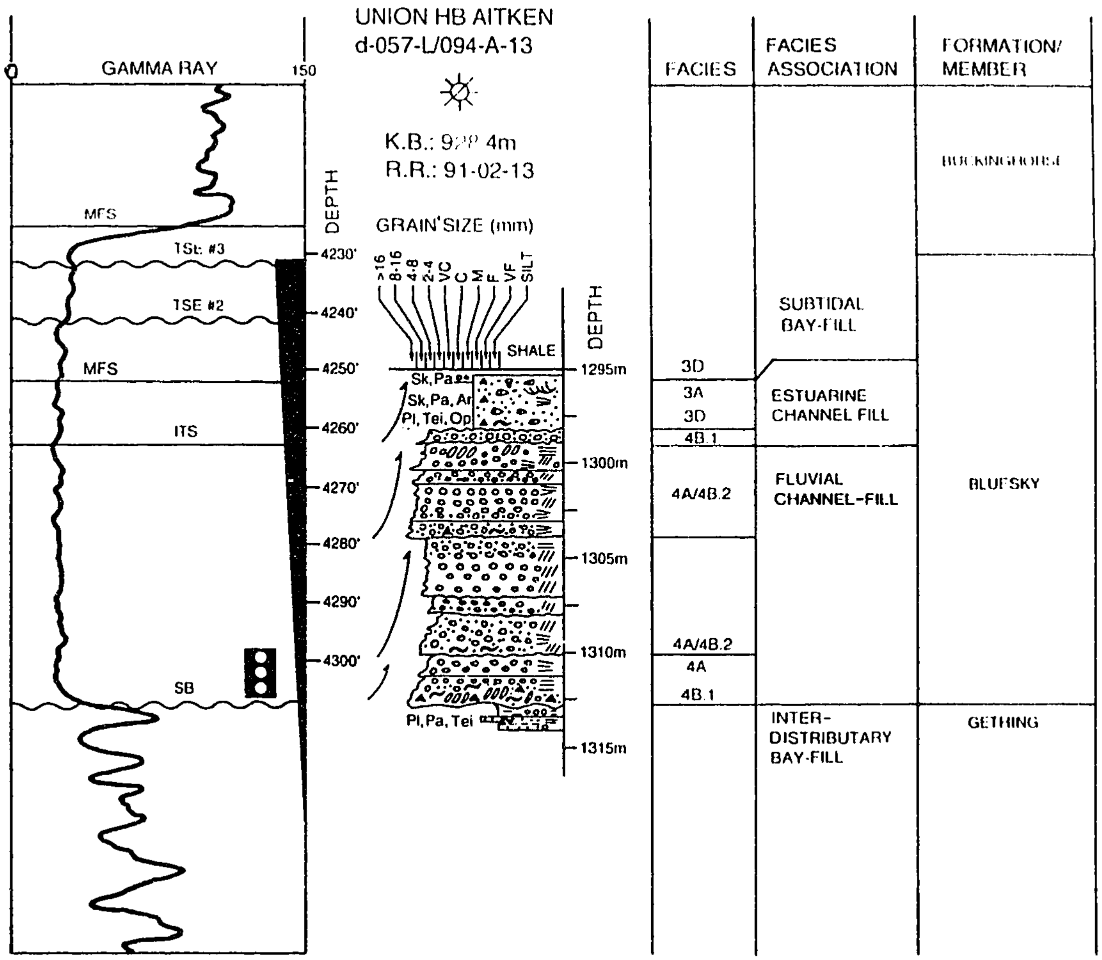


Figure 20. A. Fluvial channel-fill facies association. Channel base correlates with a sequence boundary. The channel is filled with predominantly clast-supported conglomerate and capped by the initial transgressive surface. Figure 20 A is a representative well log and core description from the Aitken Creek Field. **B.** Estuarine channel-fill facies association (see text for description and interpretation). The channel base represents the initial transgressive surface (ITS), resulting from transgression and migration of the bay-line, with the overlying facies above the channel lag illustrating tidal processes and marine influence. Refer to Table 7 for key to lithology and symbols used in diagram.

Plate 9. Representative whole core photo of the fluvial channel-fill facies association. The base of the channel fill represents a fourth-order sequence boundary (SB). Scale to lower left of photography. See Appendix A for interpretation.
Location: d-057-L/094-A-13.

Top
Facies 4A
SB
BLUESKY
GETHING
Bottom
Facies 2

polymodal, with less common, thin, bimodal and unimodal textures occuring in the upper section of a bed, in contrast to unimodal and bimodal textures common in beach settings (Nemec and Steel, 1984). The prominent shape-sorting zonation of gravel beaches, as documented by Bluck (1967) and Dobkins and Folk (1970), does not occur within the Aitken Creek conglomerates. The shape-sorting zonation conforms better to features described by Steel and Thompson (1983) in bedded conglomerates from the Triassic of Cheshire, England which reflect high-intermediate- and low waning water stage. Normal grading of beds is less common in coastal environments, and is quite common in fluvial settings. Progradational beach sequences tend to coarsen upwards in grain size (Nemec and Steel, 1984). This is not observed in conglomerate facies within the Aitken Creek Field. Conglomerates show a distinct, overall fining upward trend, and normally graded beds. Additionally, the absence of marine trace fossils and marine fauna, as well as of any evidence of tidal processes such as flaser bedding, bi-directional cross-beds, and tidal bundles, suggests that the channel-fill is fluvial-dominated (Allen and Posamentier, 1993).

The fluvial channel-fill facies association best conforms to vertical profiles of channel-fills described by Doeglas (1962); Miall (1978); Cant and Walker (1978); and by Davies *et al.* (1993) in the Lower Cretaceous Travis Peak Formation of East Texas (U.S.A.). Lateral accretion surfaces are rare and are interpreted as separating smaller, fining-upward, lateral-accreting sequences within the facies association. Lateral accretion surfaces are overlain by Facies 4B.1, which is interpreted by Jackson (1976), Allen (1984), Collinson (1986), Miall (1992) and Davies *et al.* (1993) to result from cut-bank erosion and subsequent deposition of this intraclast material along the surface. Lateral accretion structures and lateral accretion deposits (Allen, 1984) are interpreted as having developed on the inside meander bend of coarse-grained meandering streams (i.e. chute bars) as the bend widened or migrated downstream (Miall, 1992). Variably cross-stratified deposits and a fining-upward grain size and sorting trend occurring above the accretion surfaces and associated lag deposits suggest filling by a series of waning flows, possibly during flood stages of the river as the bar migrated laterally (Galloway, 1981; Cant, 1982). The grainsize decrease reflects both decreasing depth of water, and a lateral shift of the depositional site away from the main axis of the stream as the meander cut-bank was extended (Visher, 1965).

5.2.2. CHANNEL STYLE.

The vertical stacking arrangement of beds and bedsets from two detailed core descriptions located at d-034-L/094-A-13 and d-047-L/094-A-13 illustrate abundant trough cross-bedding, and lesser occurrences planar tabular cross-bedding, usually present in reaches of a fining upward cycle or sub-cycle, and horizontal bedding. Since a coarse-grained meandering stream infers low sinuosity, these conglomeratic sequences must have been at least mixed-load to bed load dominated. Thus, the sinuosity of the channels are inferred to be low, if any degree at all. Cored vertical sequences are comparable to the low sinuosity systems recognized in the Travis Peak Formation, East Texas (Davies *et al.*, 1993), and coarse-grained, low sinuosity, meandering channels inferred by Collinson (1986) and Miall (1978; 1992).

Low sinuous channels within the Travis Peak Formation are characterized by uncommon layers of intraclast conglomerates, channels which commonly stack vertically, and sedimentary structures dominated by flat bedding, high-angle, planar cross-bedding or ripple bedding, and trough cross-bedding (Davies *et al.*, 1993). In addition, flow within the low sinuous channel is not excessively flashy, as suggested by the horizontal stratification and general absence of intraclast conglomerate (Davies *et al.*, 1993).

5.2.3. WELL LOG CHARACTER

Bluesky fluvial channel-fills can easily be distinguished from Gething distributary channel-fills and Bluesky transgressive estuarine channel-fills. The gamma ray and spontaneous potential log profiles have abrupt lower contacts, smooth, blocky shape, and abrupt upper contacts. Distributary channels illustrate higher heterogeneity, with serrated bell-shaped, sharp-based profiles, and increasing gamma ray intensity upwards. Gamma ray intensity of 20 to 30 API units is indicative of a relatively clean conglomerate to pebbly sandstone. Acoustic travel time values range between 220 to 240 us/m. The gamma ray - sonic log was the most useful for correlation, because it was the log tract run in the majority of wells. However, the compensated neutron-lithodensity log shows lower density readings in conglomerate beds versus sandstone beds due to the high primary, natural gas-filled porosity preserved within fluvial channel-fill conglomerates. Although only present in wells drilled since 1990, the compensated neutron-lithodensity log is the best log tract used to distinguish between fluvial and estuarine channel-fills in wells without core data.

5.3.0. Bluesky Estuarine Facies Associations

Eight facies and two subfacies of the Bluesky Formation are interpreted to be of estuarine origin. The interpretation is based on the sedimentology, ichnology, and secondary diagenetic cements which are similar to features identified by Clifton (1982); Smith (1988); Rahmani (1988); Brownridge and Moslow (1989), Wood (1990; 1994), Allen (1991), Dalrymple et al (1992), Dalrymple (1992), Reinson (1992), Leckie and Singh (1992), and Richards (1994).

5.3.1. Estuarine Channel/ Tidal Channel-Fill Facies Association

Description The characteristic features of this estuarine/ tidal channel facies association are that it fines upward, is predominantly sandy, and contains a higher proportion of tidally influenced sedimentary structures (Fig. 20B, 21; Plate 11), and may reach up to 12 m in thickness. The lower contact of the estuarine/ tidal channel-fill represents the initial marine transgressive surface (ITS) or tidal ravinement surface (TSE #1) and is overlain by a basal conglomeratic lag (Facies 4B.1). This conglomeratic lag may be gradationally overlain by massive and deformed sandstones and pebbly sandstones containing dispersed mudstone and coal intraclasts (Facies 3D), or may pass upward directly into cross-bedded sandstones which may contain tidal bundles, flaser bedding, reactivation surfaces and sandstone dykes (Facies 3A). Interbedded sandstones and mudstones, which may be intensely bioturbated (Facies 2A), may overlie Facies 3A. Micro-faulting, glauconite, siderite and pyrite beds are common. Rootlets may be present in the uppermost part of this association. Marine trace fossils include *Palaeophycus*, *Skolithos*, *Teichichnus*, *Chondrites*, and *Planolites*. The association is capped by a marine flooding surface or ravinement surface.

INTERPRETATION: This facies association (Fig. 21) is interpreted as tidally influenced, sandy channel-fill deposits within an estuary. The lower contact of the channel fill represents the initial transgressive surface (ITS) which separates transgressive systems tract deposits, above, from lowstand fluvial valley-fill deposits below. The sharp erosional base, fining-upward trend, and abundance of large-scale cross-bedding with rip-up clasts and reactivation surfaces suggest active channel deposition. The large-scale cross-stratification (migrating sand waves and sinuous crested dunes) with interbedded small-scale cross-stratification containing mud drapes and couplets suggests highly mobile bedforms (Rahmani, 1987). Tidal bundles infer a tidal influence due to neap-spring cycles within the estuary. Several sedimentary features suggest that this facies association was deposited by moderate to strong tidal current processes within a subtidal estuarine setting. Firstly, large scale cross-stratification with mud couplets and tidal bundles have been recognized in both modern and ancient enviroments as diagnostic of tidal processes (Visser, 1980; Allen (1981, 1982), Allen and Homewood, 1984; Tillman, 1985; Kreisa and Moiola, 1986; Kessler, 1987; Ladipo, 1988; Smith, 1987; Rahmani, 1987; Brownridge and Moslow, 1991; Nio and Yang, 1991). Visser (1980) found that the mud layers were deposited during slack-water periods, with coarser grained sediments deposited during individual ebb and flood tidal events. Tidal couplets (Plate 4D) identified within trough cross-stratification of the Bluesky Formation in the Aitken Creek area are interpreted to have been deposited within a subtidal setting. The thick sand forsets record deposition during the dominant tidal

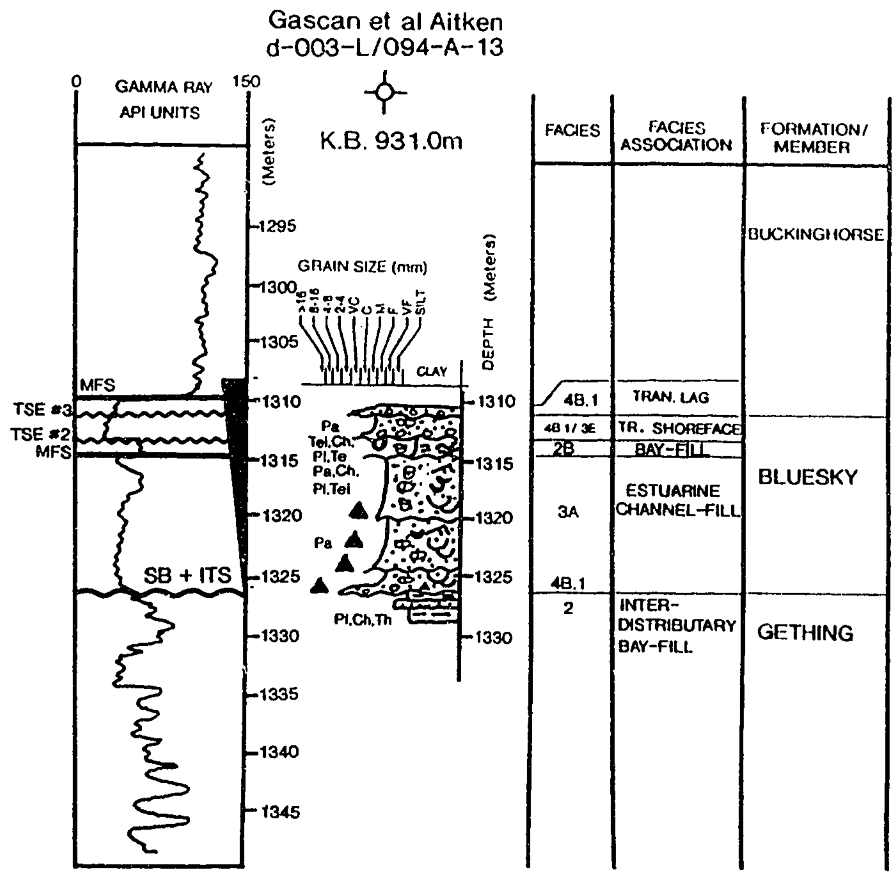
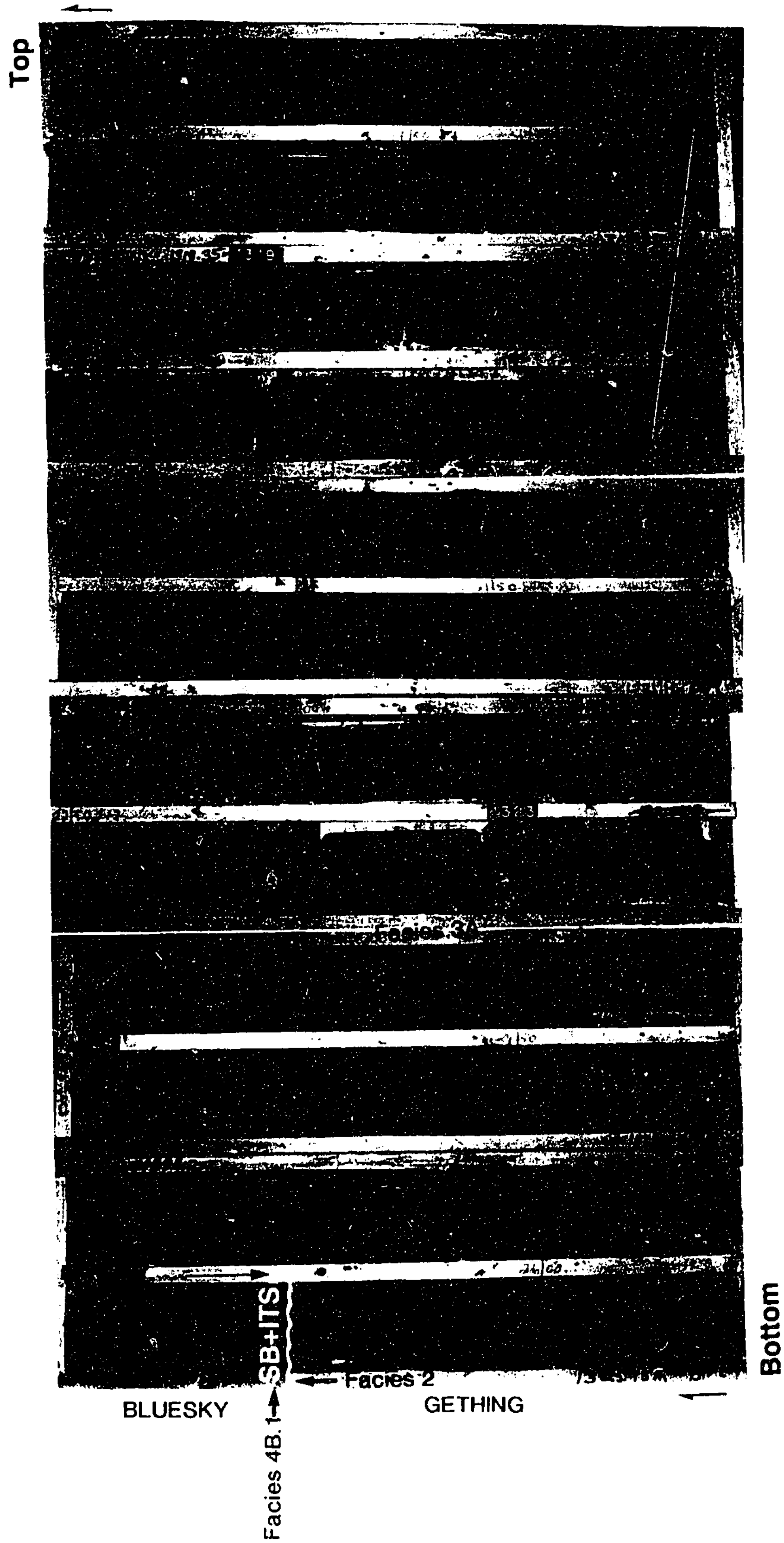


Figure 21. Estuarine channel/ tidal channel-fill facies association (see text for description and interpretation). The channel base represents an amalgamated initial transgressive surface (ITS) & sequence boundary (SB), resulting from transgression and migration of the bay-line, with the overlying facies above the channel lag illustrating tidal processes and marine influence. The upper contact represents a marine flooding surface (MFS) with the overlying estuarine bay-fill facies association. Refer to Table 7 for key to lithology and symbols used in diagram.

Plate 10. Representative whole core photograph of the estuarine channel/ tidal channel-fill facies association. Base of the channel is an amalgamated sequence boundary (SB) and initial transgressive surface (ITS). Lower sandstones contain abundant tidally-influenced primary sedimentary structures (i.e. tidal couplets).

Scale: One core box is 5 ft or 1.54 m.

Location: d-003-L/094-A-13.



Top
Bottom
SB+ITS
Facies 4B.1
Facies 2
BLUESKY
GETHING

current, with the thinner sand foresets, sandwiched between the two thin mud layers, infers deposition during the subordinate tidal current.

A subtidal channel setting for this estuarine/ tidal channel-fill facies association is additionally inferred from the density and distribution of burrow traces within finer grained beds of channel sandstones, combined with the complete absence of dessication features.

The upward changes in grainsizes, scale and type of cross-stratification in estuarine channel/ tidal channel-fill deposits within the Aitken Creek study area may reflect a vertical succession of facies corresponding to a decrease in tidal current velocities or the shifting locus of deep and shallow water tidal flows. The transition upward from large-scale cross-stratified sandstones with tidal bundles to small-scale cross-stratified sandstones and mudstones implies decreasing flow velocities, shallowing of the water column, and progressive abandonment of the active channel, which then becomes replaced by estuarine point bar/ abandoned estuarine channel (Section 5.3.3.) or tidal flat deposits. Synaeresis cracks are interpreted as representing fluctuations in salinity (Burst, 1965). The upper interbedded sandstone and mudstone interval overlying active channel-fill deposits is predominantly sandy, with rare interbeds of thin siltstone and mudstone. Sandstone beds are dominated by tidal bedding consisting of bimodal asymmetrical ripple cross-lamination, herringbone cross-bedding, flaser bedding and wavy bedding, with local intensely bioturbated interbeds. The primary sedimentary features infer bimodal, tide-induced currents with minor wave processes. Higher up section within the intertidal flat, sandtone and mudstone interbeds obtain approximately similar thicknesses.

In addition, symmetrical ripple laminations occur with higher frequency compared to asymmetrical ripple cross-laminations infering an increase in wave processes, with secondary effects by tidal currents. Where present, the uppermost deposits are relatively muddy, strongly bioturbated, with rare thin interbeds of sandstone, display root traces or coal beds and are interpreted as upper intertidal (Clifton, 1982). The abrupt upper surface of the estuarine channel/ tidal channel facies association is a marine flooding surface.

The formation of sandstone dykes, or fluid escape structures, within the large-scale trough cross-stratification of d-003-L/094-A-13 has been discussed by Allen (1984) and Nichols *et al.* (1994). Fluid escape structures suggest rapid deposition of loosely packed sediments and dewatering, recording the movement of the pore fluid during depositon. Fluid escape structures form when the vertical pore water flow through a layer of non-cohesive granular sediment can cause partitioning into a lower fluidized region and an upper static couplet, separated by a water-filled crack which distorts into a discrete water filled void. The voids then rupture and water/sediment mixture bursts through the rupture produce a fluid escape structure (Nichols *et al.*, 1994).

One disturbing problem within the estuarine channel/ tidal channel facies association is the absence of mixed marine and brackish water faunas as channel lags. Shell debris lags are considered common features of modern tidal channel and estuary deposits (Kumar and Saunders, 1974; Barwis and Makurath, 1978; Weimer *et al.*, 1983; Frey and Howard, 1986; Allen, 1991). However, the absence of shell debris within channel lags from the Bluesky Formation may be a function of removal by diagenetic processes (Stephens *et al.*, 1973; Thomas *et* *al.*, 1987). By comparison, the channel-floor deposits of the tidally influenced Ogeechee River (Georgia) consists of clean coarse sand, trough cross-bedded sands, without shells or shell fragments (Greer, 1975; Thomas *et al.*, 1987). This implies that shells and shell fragments may be uncommon features within tidally influenced rivers and suggests that their absence in ancient deposits does not necessarily mean lack of marine influence (Thomas *et al.*, 1987).

The rare-to common occurrence within cross-bedded sandstones of biogenic structures that are lined suggests an ecologically stressful environment. Within some intervals of large-scale cross-stratification, a low density and low diversity monospecific assemblage of *Palaeophycus* burrows weakly disrupts the sedimentary features within the active channel. *Palaeophycus* burrows infer an environment with high sedimentation rates and relatively high current velocities. Due to the high current and/ or wave energy of this facies, little food will be deposited , therefore the predominant horizontal burrows in this environment will be occupied by mobile carnivores searching the substrate for food. Reduction in current and/ or wave energy of this facies results in the re-establishment of a equilibrium suspension- and deposit feeding community. The establishment of a deposit feeding community within finer grained mudstones results during slack-water periods of the tidal cycle, when wave processes or tidal currents are at their lowest.

An estuarine channel interpretation for this facies association is consistent with its stratigraphic position overlying fluvial channel deposits and based on modern studies of estuaries. The Wallapa Bay estuary on the southwestern coast of Washington was described by Clifton and Phillips (1980) and Clifton

(1982). They illustrate a vertical succession of facies (Fig. 22) that are similar in respect to the vertical association of facies within the subsurface of the Aitken Creek study. Additionally, the estuarine/ tidal channel facies association within the Aitken Creek study is similar to the cross-bedded facies of Oomkens and Terwindt (1960) described from the Holocene Haringvliet Estuary in the Netherlands. The facies was interpreted as subtidal channel fills occupying an area within the estuary dominated by flood tidal currents upto 82 cm/sec, and subordinate ebb tidal currents upto 44 cm/sec in velocity (*in* Rahmani, 1988, p. 446). Recently abandoned subtidal channels in the Oosterschelde Estuary, southwesten Netherlands was studied by van der Berg (1980) were shown to occupy a scour pit upto 15.0 m in depth. The lower 6.0 m of the channel fill contained cross-bedded sands. This facies illustrated bimodal-bipolar paleoflow, with ebb dominant tidal currents, and well preserved mud couplets and tidal bundling (Visser, 1980; van der Berg, 1980) similar to facies in estuarine/ tidal channel deposits within the Aitken Creek study area. The upper nine meters of the abandoned channel in the Oosterschelde Estuary consisted of horizontal stratification. Subsurface examples documented in Brownridge and Moslow (1991) and Wood (1990; 1994) in the Glauconite Member of the Mannville Group, Alberta and by Leckie and Singh (1992) in the Peace River Formation, Alberta describe features similar to the tidally influenced facies observed within the Bluesky Formation. Outcrop examples of estuarine channels with features similar to estuarine/ tidal channel deposits within the Aitken Creek study area are described by Richards (1994) in the lower Triassic at Barles, Alpes des Haute Province, France.

Wood (1990; 1994) illustrates similar distinction between tidal channels and

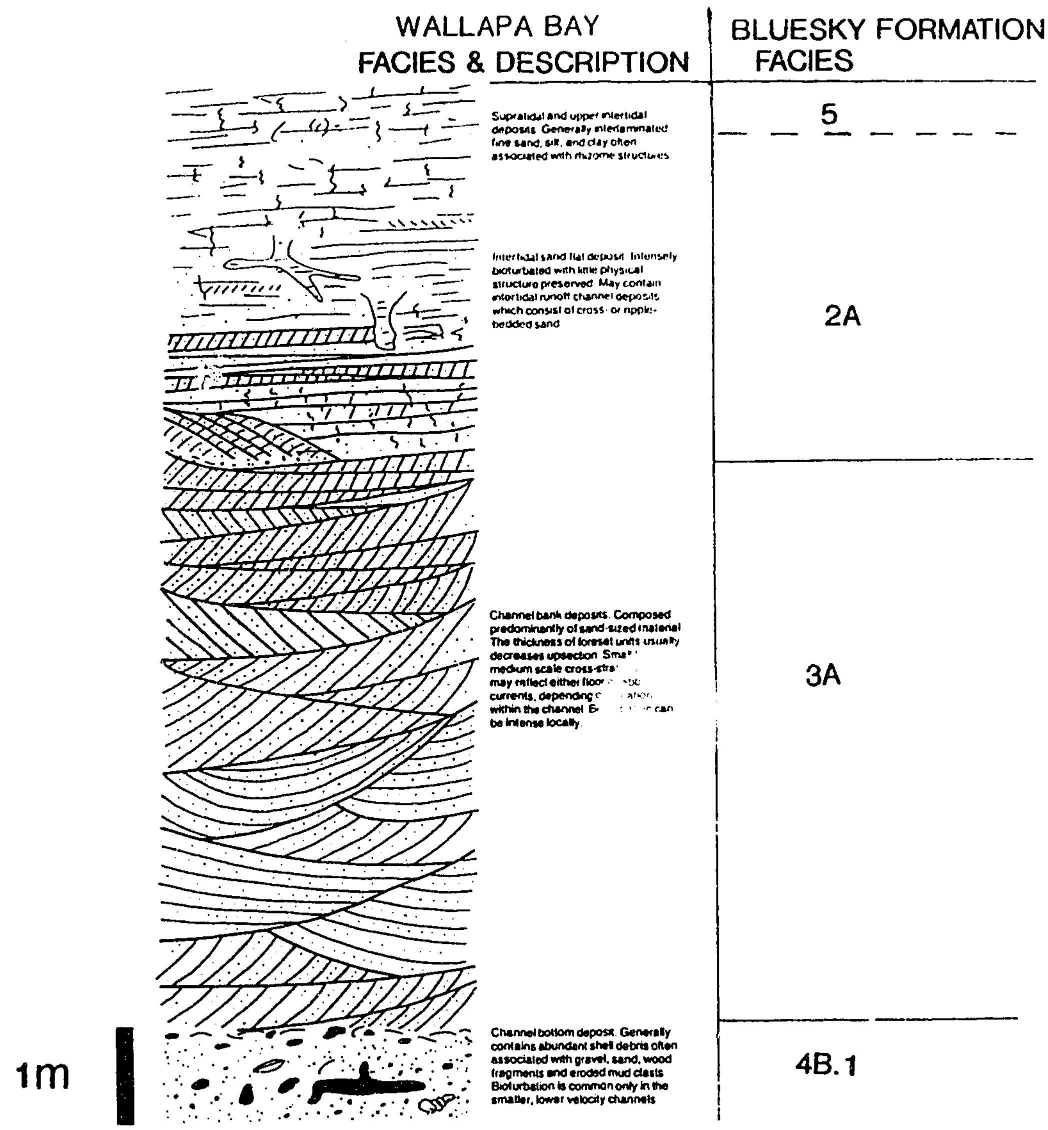


Figure 22. Estuarine Channel fill from the Wallapa Bay Estuary, Washington. (Modified from Clifton, 1982).

active estuarine channels based on stratigraphic position, thickness and sedimentary features within the vertical facies association in the Glauconite Sandstones of central Alberta. Thick channel deposits of the estuarine/ tidal channel-fill facies association are interpreted as thick, aggrading estuarine channel deposits located within the upper to middle estuary within a riverine estuarine complex (Smith, 1988; Leckie and Singh, 1992; Bechtel et al, 1994; and Beynon, 1994). Wood (1990) interprets thinner, tidal channel deposits of the Glauconite Sandstone as inter-valley deposits representing the outer estuarine embayment. The significance of the stratigraphic position of the two channel types will be discussed in section 6.0.0 on sequence stratigraphy.

5.3.2. WELL LOG CHARACTER

The gamma-ray log profile is cylindrical or bell shaped and serrated, with abrupt lower and upper contacts (Fig. 21). Cylindrical profiles, with relatively uniform low API Unit recordings (approximately 25 API) infer clean sandstones. Very low radioactivity levels infer the absence of radioactive minerals which may have originated from volcanic ash, granite wash, or radioactive charged subsurface fluids (i.e. Pardonet/ Baldonell Formations of northeastern British Columbia (*In* Barss and Montandon (1980)). Bell shaped profiles and API Units increase in value upwards from 30 to 45 API infer increasing argillaceous content upwards within the log profile of the facies association. The sonic log is characterized by linear shapes, consisting of open or tight serrate profiles and/or a combination of both. Interval travel times range between 155 us/m to 163 us/m and are consistent with velocities characterizing clastic deposits. Spontaneous potential log tracts are characterized by smooth, linear profiles, with negative deflections of upto -47 mV from the inferred shale base line. This reflects formation water salinity which is greater than the mud filtrate salinity, inferring permeable salt water sandstones.

5.3.3. Abandoned Estuarine Channel-Fill/ Point Bar Facies Association

DESCRIPTION: This facies association fines upward and contains a higher proportion of marine facies than the estuarine channel/ tidal channel-fill facies association. Typically this unit is on the order of 3.0 to 12.8 m thick (Fig. 23; Plate 11). The basal contact of the channel fill is erosional and/ or burrowed and represents the initial transgressive surface, separating transgressive systems tract deposits, above, from lowstand fluvial valley fill deposits below. This surface is overlain by a basal conglomeratic lag (Facies 4B.1) that passes upwards into a thin unit of cross-bedded sandstones with tidal bundles (Facies 3A). These are in turn overlain by a thick unit of lenticular, wavy, and flaser-bedded, very fine- to medium-grained sandstones, siltstones, and mudstones (Facies 2). Where sandstone beds are not obscured by bioturbation they contain parallel laminations, current- and combined-flow ripples, bimodal asymmetrical ripple cross-lamination, and, in places, rare wave ripple laminations and reactivation surfaces. Mudstone interbeds contain synaeresis cracks and rootlets. Interbedded units are inclined at angles between 0 to 12 degrees. Internally, interbedded sandstone and mudstones may be disrupted by scour surfaces defined by carbonaceous mudstone and coal intraclasts. The characteristic feature of this facies association is the cyclic alternation between sandstone and mudstone. Bioturbation intensity is variable in the upper parts of this facies association, but typically is low or absent. Interbedded, very fine-grained sandstones, siltstones, and mudstones decrease in silt and sand content,. grading upwards into massive silty mudstones (Facies 1), in turn overlain by rooted, bioturbated silty to sandy mudstones (Facies 2B), carbonaceous mudstones or coals (Facies 6), and capped by a transgressive surface of erosion or marine flooding surface.

INTERPRETATION: The stratigraphic position of this facies association with respect to laterally equivalent estuarine channel fills and other facies associated with underlying marsh/ swamp deposits (Facies 6A), or lowstand fluvial channel conglomerates suggest that this facies association represents lateral accreting point bars and abandoned channel fills. The vertical association of facies is similar in respect to the described vertical association of facies for the migrating channel within the main tidal channel in the mesotidal Willapa Bay estuary, Washington (Fig. 24) (Clifton and Phillips, 1980; Clifton, 1982; Smith, 1988). The base of the abandoned estuarine channel-fill/ point bar facies association is either erosional or burrowed.

Where burrowed, the contact is characterized by robust, unlined, oblique to branching burrows, passively infilled with material similar to Facies 4B.1 and Facies 3A, extending downward into the underlying interdistributary bay-fill deposits of the Gething Formation (Plate 12). Biogenic structures are identified as *Skolithos* or *Arenicolites* (?), and represents the *Glossifungites* ichnofacies. The *Glossifungites* ichnofacies has been studied in modern environments by Pemberton and Frey (1985) and numerous subsurface examples compiled in MacEachern *et al.* (1992) and Pemberton *et al.* (1992).

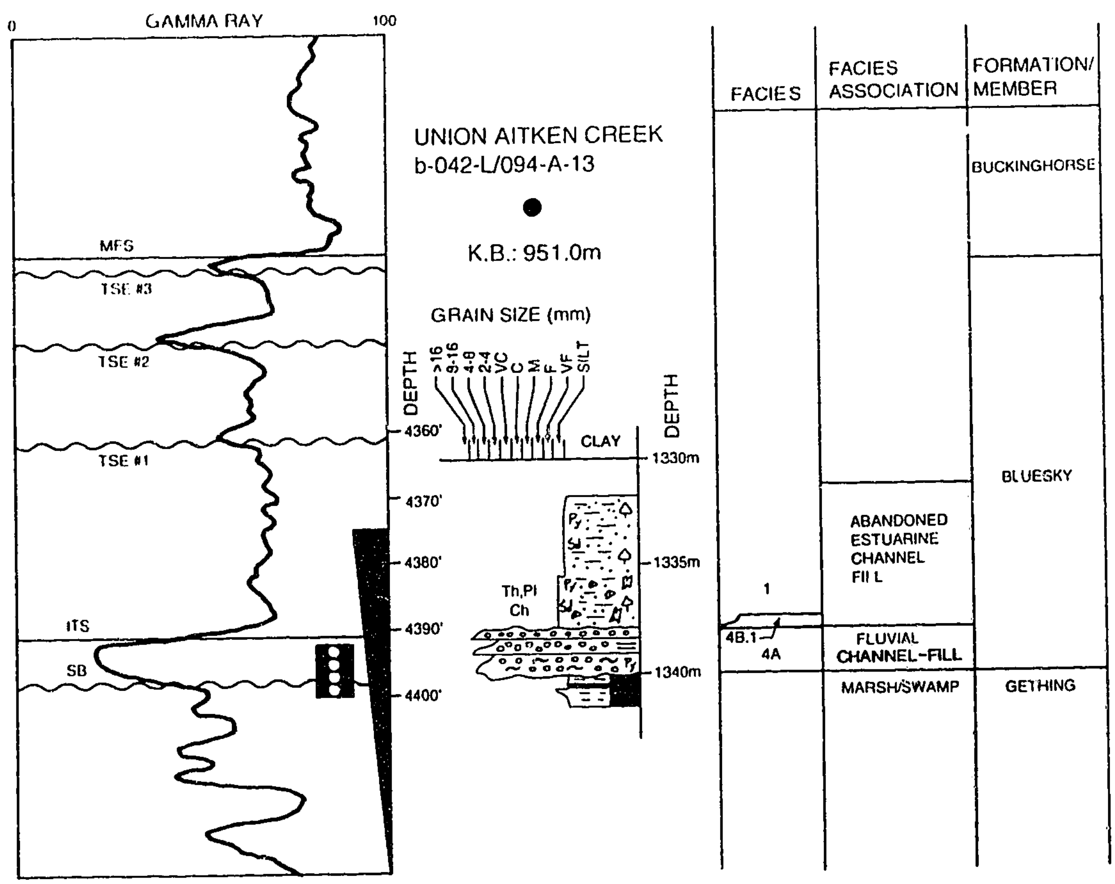


Figure 23. Abandoned estuarine channel-fill/ point bar facies association. The channel base (ITS) results during transgression and migration of the bay-line above the fluvial channel-fill facies association (see text for description and interpretation). The overlying facies above the estuarine channel lag illustrate progressive abandonment of the channel and filling by suspension fallout. Refer to Table 7 for key to lithology and symbols used in diagram.

Plate 11. Whole core photography of the abandoned estuarine channel-fill/ point bar facies association. This photograph shows lowstand fluvial channel fill conglomerate overlain by a channel lag and massive silty mudstones. The contact between the two is the initital transgressive surface (ITS).
Location: b-042-L/094-A-13.

Top

Bottom

Thomas *et al.* (1987) suggest where the cutting and filling events in the history of a given channel are widely separated in time, some lateral accretion deposits may overlie non-contemporaneous erosion surfaces. Biogenic structures are interpreted to represent suspension-feeding annelids which favour the higher energy, shifting substrates, and agitated waters of the active subtidal channel. The emplacement of the substrate-controlled ichnofacies may be associated with the high energy channel cut bank side of the abandoned estuarine channel/ point bar facies association (Plate 12), and subsequently bec::ne passively in-filled with facies 4B.1. By comparison, Pemberton and Frey (1985) observed similar features in exhumed saltmarsh muds cropping out along back-barrier streams adjacent to Petit Chou Island (Georgia Coast, U.S.A.). The saltmarsh muds have been exhumed by lateral erosion of the tidal channel which are colonized by opportunistic estuarine trace making organisms of the *Glossifungites* ichnofacies. The presence of a substrate-controlled ichnofacies along the cut-bank of the meandering channel illustrates the limited areal extent of the *Glossifungites* ichnofacies and its relative unimportance in terms of the definition of surfaces of sequence stratigraphic importance. This suggests that the emplacemt of the *Glossifungites* ichnofacies can occur on a limited or over a wide geographic extent, with the latter being important in terms of recognition of key sequence stratigraphic surfaces (S.G. Pemberton, pers. comm., 1994).

The abandoned estuarine channel-fill/ point bar facies association shows the active portion of the channel (Facies 4B.1 and Facies 3A) is relatively thin (0.5 m) (Fig. 23). The presence of higher amounts of intraformational-derived clasts relative to chert pebbles, supports the genetic affinity between substrate erosion and emplacement of this sublithofacies (MacEachern *et al.*, 1992). This channel-floor material tends to be thinner, the sideritzed mudstone and carbonaceous mudstone and coal intraclasts tend to be angular to rounded. The polymodal and polymictic texture suggest that particles were locally derived (i.e. cut-bank cavings and erosional slumping; reworking of previously deposited dessicated mud-drapes on point bar surfaces; undercutting and downslope movement of large "rafts" or "sheet" blocks of inclined units) and transported short distances, with very little to no reworking by currents, before deposition. Thin, massive bedded, matrix-supported polymodal conglomerates infer very rapid depositon. Channels and laterally migrating bar complexes above suggest that the lag formed at the base of a channel under upper flow regime transport in unidirectional flow; this is its typically stratigraphic context. Where transitional upward into Facies 3A, this suggests decreasing flow velocities, and the depositon of lower flow regime dunes within a subtidal setting (Rahmani, 1988).

Facies 4B.1 and/ or 3A passes upwards into sediments deposited by alternating bedload traction and suspension fallout deposits, thus inferring tidal processes. The sedimentary features of an estuarine point bar facies association are inclined heterolithic stratification deposition on laterally accreting point-bars of the upper to middle estuary or intertidal to subtidal creeks within the incised valley (Thomas *et al.*, 1987; Smith, 1988). Modern and ancient examples of IHS have been recognized by Oomkins and Terwindt, 1960; Howard *et al.*, 1975; Horn *et al*, 1978; Puigdefabregas and van Vliet, 1978; de Mowbray, 1983; Flach and Mossop; 1983; Smith, 1985; Rahmani, 1988; MacEachern, 1989; Leckie and Singh, 1992; Shanley *et al.*, 1992. The above interpret IHS as the product of lateral accretion deposits within migrating point bars.

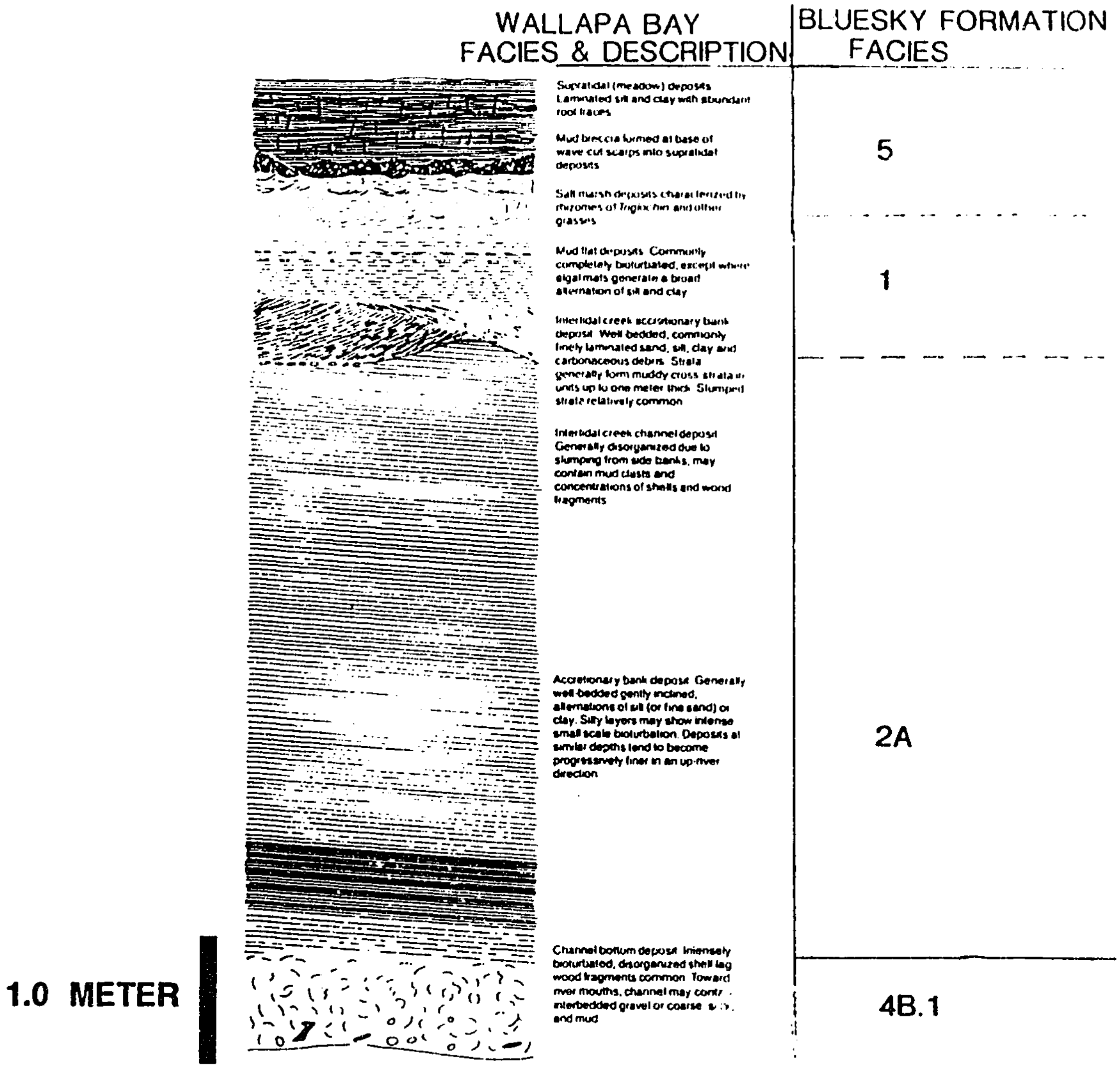


Figure 24. Vertical profile of laterally accreting channel fill deposits from the Wallapa Bay Estuary (modified from Clifton, 1982).

Plate 12. Burrowed contact along the cut-bank of an abandoned estuarine channel. Trace fossils are interpreted as *Skolithos* or *Arenicolites* ? (Sk or A) and represent the *Glossifungites* ichnofacies. Scale bar is in cm. Location: d-024-L/094-A-13, 1348.7-1348.85 m.

Vertical sequences observed in wells a-005-L/ 094-A-13 and c-028-F/094-A-14 (Appendix A) contain a basal channel fill unit consisting of moderately sorted, trough cross-bedded sandstone with mud drapes or mud couplets interpreted as lower pointbar deposits. This is transitional upwards into sand-dominated IHS deposits, with sandstone and mudstone couplets tens of cm thick. Sandstones are sharp-based or scoured and either grade into or are abruptly overlain by carbonaceous mudstone laminae and/or interlaminated sandstone and mudstone. Mudstones interbeds are typically moderately to intensely burrowed. This interval is interpreted as a middle point bar deposit, similar to those interpreted by Beynon (1994) and Bechtel *et al.* (1994). Sand dominated IHS, in some cores, is gradationally overlain by a section of mud dominated IHS. Sandstone content and thickness of very fine-grained sandstone and siltstone beds decrease upwards. This is interpreted as upper point bar deposits and are similar to deposits interpreted by Beynon (1994) and Bechtel *et al*. (1994).

Internal deformation features are characterized by syn-depositional gravity faults and infer rapid deposition on a sloping surface. Within point bar deposits of a tidal gulley on an intertidal flat, Jade Bay (North Sea), gravity faults with curved surfaces are produced during rapid sediment deposition. The multiple scour surfaces, by comparison, may have formed under circumstances similar to those described by deMowbray (1983) in lateral accretion deposits of point bar sequences from Solway Firth, Scotland. Lateral accretion deposits are considered by deMowbray (1983) to

> " form a series of wedge-shaped units. Each unit represents one year's deposition, bounded by erosional scarps produced during sucessive winters".

The multiple scour surfaces within pointbar deposits of the Bluesky Formation may have formed from similar weathering conditions as described from Solway Firth (Scotland) or produced by episodic storm tidal surges

Facies 2 is replaced laterally by massive silty mudstones o [illegible] 1. Massive silty mudstones are carbonaceous and fine upwards becoming progressively muddier, reflecting abandonment of the channel and infilling by suspension fallout. Thick silty mudstone deposits described in d-042-L/094-A-13 shows a significant reduction in burrowing within the upper two-thirds of this facies infering anoxic bottom conditions, suggesting a restricted marine setting with moderate oxidation and slight anoxia. This was additionally confirmed by the palynomorphs sampled from this facies. Siderite forms when intersitial pore waters become depleted with respect to free oxygen and dissolved sulfur, suggesting anoxic or reducing conditions. Its presence in this facies suggests rapid accumulation and decomposition of organic material in a restricted, anoxic or oxygen depleted setting (Pye, 1981). It is difficult to speculate if the overlying water column was oxygen depleted. However, the low density and diversity of biogenic structures present, coupled with the abundance of siderite and cabonaceous nature of this facies suggests the interstitial pore waters were poorly oxygenated. The absence of biogenic structures produced by suspension-feeding organisms could result from low salinity which may have imposed a physiological stress or the physical and ecological conditions of the depostional environment could not sustain a suspension-feeding community.

Zones deficient of biogenic structures imply that periodically, anoxic conditions may have been re-established or prolonged periods of oxygen depletions would be lethal to benthic organisms (Beynon *et al.*, 1992).

The IHS sets and laterally adjacent mud plugs infer local meandering of the estuarine channel, channel abandoment and the development of oxbow lakes. By comparison, the abandoned estuarine channel/ point bar facies association is similar in many respects to the meandering channels within the macrotidally-influenced upper reaches of the South Aligator River, Australia (Woodroffe *et al.*, 1989) and subsuface meandering channels of the Glauconite Formation, Alberta (Wood, 1990; Brownridge and Moslow, 1991) and Peace River Formation, Alberta (Leckie and Singh, 1992). The development of channel plugs and oxbow lakes occurs when the estuarine meandering channel becomes slowly plugged. Sediment influx into the abandoned channel occurs during turbid, overbank, freshwater flow during flood discharge into the estuary. The accumulation of suspended material (i.e. silt, clay, organic remains) within the channel plug occurs slowly and periodically due to flood events within the estuary. The weak bioturbation and rare occurrences of *Planolites, Thalassinoides* and *Chondrites* implies the trace making organisms within the channel plug may be the result of organisms entrained with the sediment in the flood waters during tidal storm events which would overwhelm the fresh water lense within the estuary (Ranger and Pemberton, 1992).

The uppermost deposits of this facies association, where preserved and not removed during ravinement, are characterized by abundantly rooted bioturbated sandy mudstones, carbonaceous mudstones and coals interpreted as tidal flat deposits. The upper contact represents either a marine flooding surface or ravinement surface produced during continued transgression of the Moosebar/Wilrich Sea.

An upper- to middle subtidal estuarine interpretation (Clifton, 1982; Smith, 1988; Rahmani, 1988) is consistent with the stratigraphic position of this facies association, which is laterally adjacent to the estuarine channel/ tidal channel-fill faices association, and immediately overlies a marine flooding surface identified as the initial transgressive surface (ITS) and underlies a marine flooding surface (MFS) or transgressive surface of erosion (TSE). Additional evidence is found in the abundant but not diverse trace fossil assemblage and palynomorphs suggesting a stressed ecological setting. This would occur in the upper to middle reaches of a riverine estuary where shifting substrate and fluctuations in turbidity, salinity, and temperature are common (Dorjes and Howard, 1975; Ekdale *et al*, 1984; Frey and Howard, 1986; Leckie and Singh, 1992).

5.3.4. Well Log Character

The gamma-ray log profile is bell shaped or linear and serrated, with abrupt lower and upper contacts (Fig. 23). Bell shaped profiles and API Units increase in value upwards from 30 to 75 API infer increasing argillaceous content within the log profile of the facies association, higher API values than sandy estuarine channel profiles. The sonic log is characterized by linear shapes, consisting of open or tight serrate profiles and/or a combination of both. Interval travel times range between 155 us/m to 165 us/m and are consistent with velocities characterizing clastic deposits. Spontaneous potential log tracts are characterized by smooth, linear profiles, with negative deflections of upto -20 mV from the inferred shale base line.

5.3.5. SUBTIDAL ESTUARINE BAY-FILL FACIES ASSOCIATION

DESCRIPTION: This facies association shows both fining and coarsening upward trends and contains a higher proportion of marine facies than either estuarine channel/ tidal channel-fill or abandoned estuarine channel/ point bar facies associations. The subtidal estuarine bay-fill facies association may reach up to 5 m in thickness. The lower contact of the bay-fill is a marine flooding surface (MFS) which is overlain by bioturbated sandy mudstone (Facies 2B) massive silty mudstones (Facies 1) and grading upwards into either cross-bedded sandstones (Facies 3A), or parallel-laminated sandstones (Facies 3D) (Fig. 25A; Plate 13). Interbedded and interlaminated very fine- to medium-grained sandstones, siltstones and mudstones interstratified with bioturbated silty and sandy mudstone intervals, synaeresis cracks and, in some places, rootlets either display fining- or coarsening upward trends (Facies 1, 2A, and 2B). Fining upward sucessions contain a lag (up to 50 cm thick) marking the base of the sequence (Facies 4B.1). The trace fossil assemblage includes *Terebellina, Chondrites, Planolites, Teichichnus, Skolithos, Palaeophycus*, and *Asterosoma*. The subtidal estuarine bay-fill facies association is capped by a transgressive surface of erosion (TSE) from continued transgression of the Moosebar Sea and flooding of the incised valley.

INTERPRETATION: This facies association is interpreted as a subtidal estuarine bay-fill and commonly observed within the middle to upper Bluesky Formation within the study. The coarsening upward trend in grainsize and the reduction of mudstone content and bioturbation infer increased energy levels related to either shallowing of the water column and/or progressive infilling of the brackish water bay in an estuarine embayment. Similar estuarine bay-fill sucessions have been described and interpreted from subsurface Cretaceous examples by Reinson *et al.* (1988), Clark and Reinson (1990), Pattison (1992), Pemberton *et al.* (1992), and Beynon (1994). The highly bioturbated sandy mudstone and massive silty mudstones facies are carbonaceous and reflect relatively slow deposition within a brackish environment. The trace fossil suite present infers that marine conditions were established, however, the low diversity and abundance, and in some instances, a decrease in ichnofossil size from their fully marine counterparts (i.e. *Terebellina*) suggests that fully marine conditions were not established in the lower sections of the bay fill. The interbedded and interlaminated sandstones and mudstones record periods of either seasonal flood discharge or storm surges into the estuarine bay when coarser grained material was transported by traction currents, and subsequently capped by suspension fallout of mudstones during re-establishment of fair-weather conditions. The abundance of synaeresis cracks and a low diversity of ichnofossils in the mudstone laminae and beds is indicative of deposition within a fluctuating, brackish water environment. The upward coarsening and thickening packages of sandstone are interpreted to reflect the later stages of the bay-fill cycle as represented by the development of extensive subtidal shoals/ sand sheets and sandflats. Thicker, normal graded, parallel-laminated and trough cross-bedded sandstones represent depositon from tidal currents, and possible enhancement by storms, during upper and lower flow regime conditions (Richards, 1994). Oscillatory currents are inferred where trough

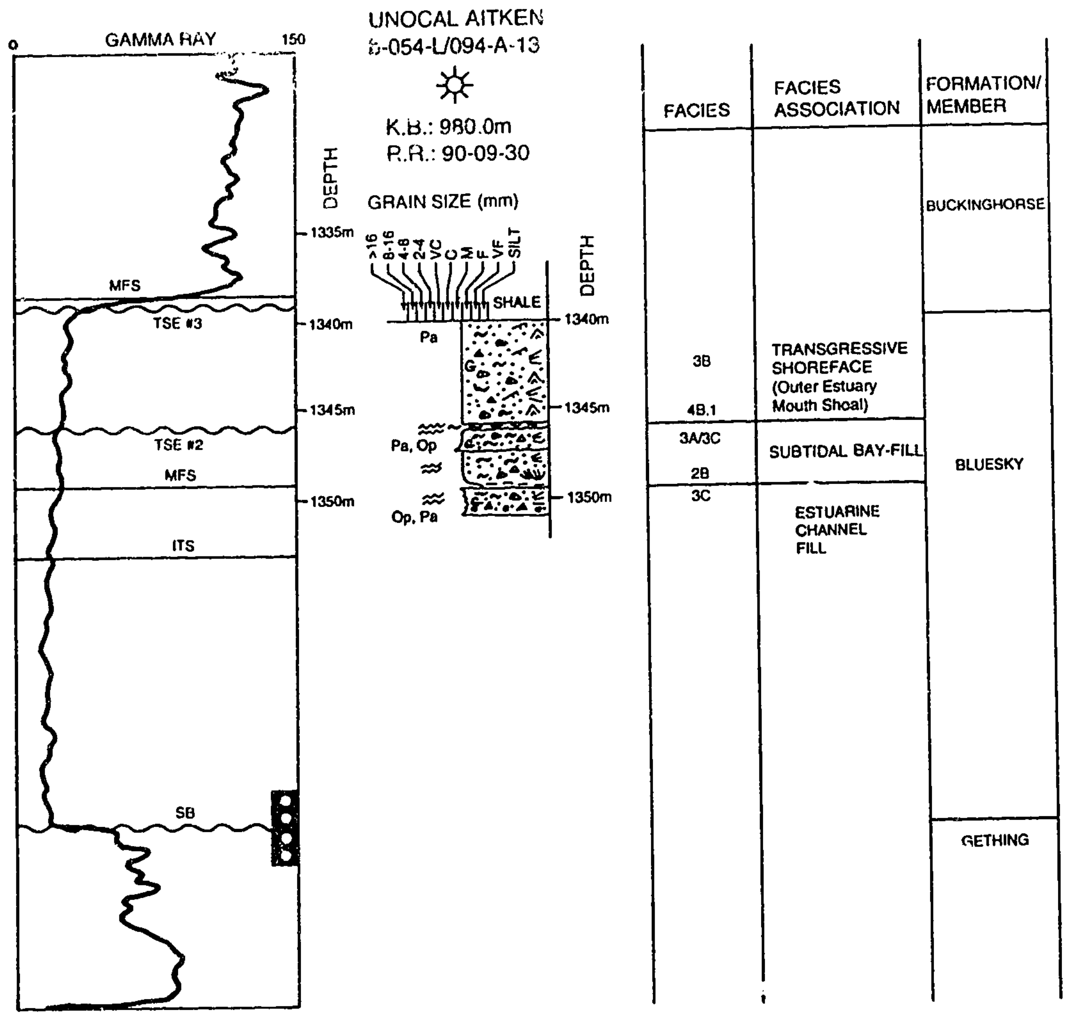
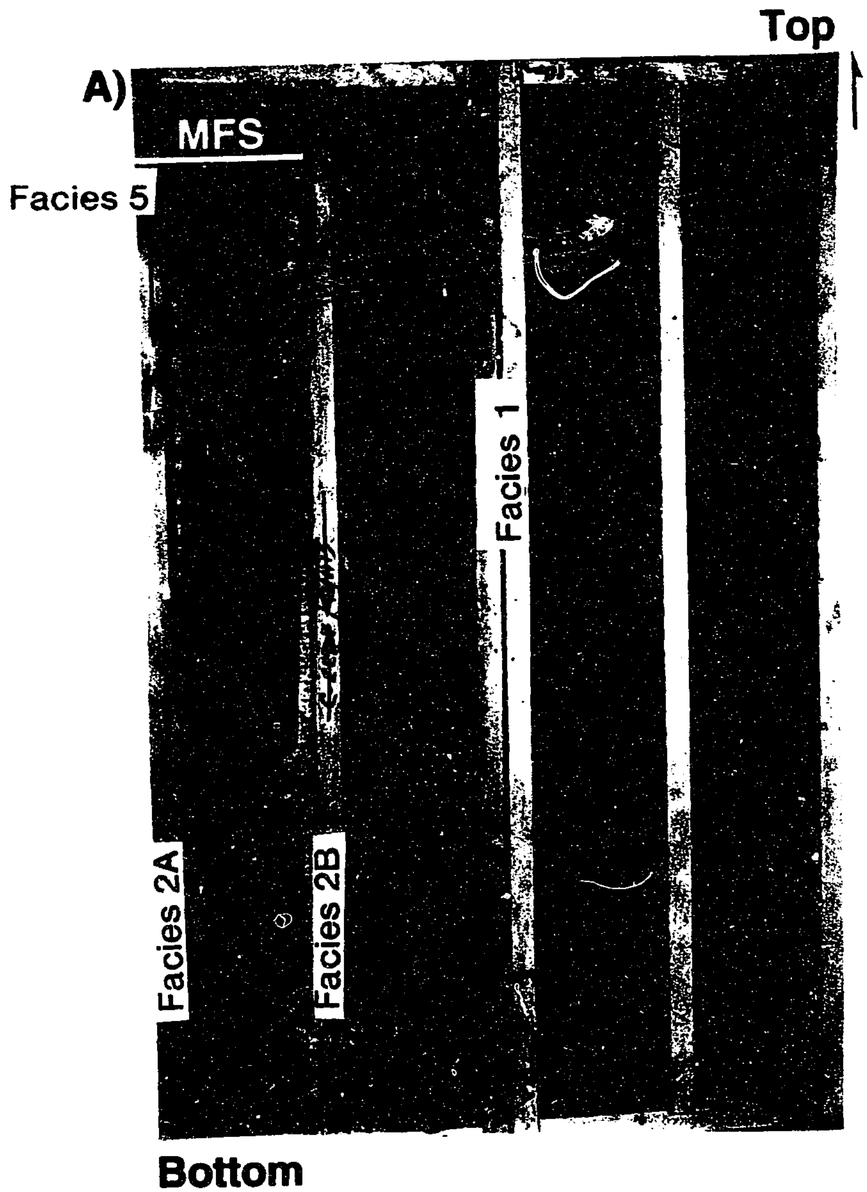


Figure 25. **A.** Subtidal estuarine bay-fill facies association is bounded by a marine flooding surface (MFS) below and a ravinement surface above (TSE). **B.** Transgressive shoreface facies association (see text for description and interpretation). The coarsening and fining upward transgressive shoreface succession is capped and underlain by a wave ravinement surface (TSE). Refer to Table 7 for key to lithology and symbols used in diagram.

Plate 13. Representative cores of the subtidal estuarine bay-fill facies association. The cores show the two end members of this association. Sandstones facies are characterized by shoals (A) and mudstone dominated intervals are characterized by estuarine bays (B). Scale: one core box is 5 ft or 1.54 m Locations: (A) d-044-L/ 094-A-13, 4406'-4410';(B) c-028-F/ 094-A-13, 1273.65-1276.9m .


A)
Top
MFS
Facies 5
Facies 1
Facies 2A
Facies 2B
Bottom


B)
Top
Bottom

cross-bedded sandstones are underlain by interstratified intensely burrowed sandstones and thin, wave ripple cross-laminated sandtones, which clearly indicate wave processes within the estuary. Glauconite is interpreted to have formed within the estuarine bay, where there is some turbulence, low sedimentation rates, slightly reducing conditions, and some organic matter (Reineck and Singh, 1982). Sub-environments within this facies association probably included lagoons/bays, subtidal to intertidal sand flats and sand sheets/shoals, inter-shoal areas.

Fining upward sequences less than 5 m thick, which are inferred from gamma ray log prifiles, are interpreted as tidal channels/creeks, and tidal point bars dissecting shoal/ sand flat sandstones and lagoon/ bay deposits within the estuary. A facies association for tidal channel/ creeks is discussed within section 5.3.7 and 5.3.9 under active estuarine channel/ tidal channel and abandoned estuarine channel/ point bar facies associations.

The presence of primary sedimentary structures inferring storm and/ or wave processes indicates that subtidal estuarine bay-fill facies association was open to the Moosebar/Wilrich Sea. However a strong fluvial or freshwater input into the estuarine bay is interpreted from brackish water indicators preserved within the sediments. The bay is interpreted in an setting with an open, but restricted , open connection to the Moosebar/Wilrich Sea. Such a restricted opening would effectively amplify nearshore wave and tidal effecst such that they are preserved in the sedimentary record several tens of kilometers inland from the open coastline (Beynon, 1994). This facies association is either transitional paleoseaward into estuary mouth sandstones or is overlain by outer estuary and shoreface sandstones and conglomerates, implying flooding of the valley and landward migration of the shoreface and estuary mouth over bay-fill deposits.

5.3.6. WELL LOG CHARACTER

The gamma ray log is used to identify subtidal bay-fills on well logs. As a result of the high mudstone content, the gamma ray profile has a high API value. Profiles are either bell-, funnel-, or linear in shape. The gamma ray profile for this facies assemblage is easily distinguished from underlying valley-fill deposits which have characteristically lower API values. An exception to this is the mud plugs within the upper- to middle estuary.

5.4.0. BLUESKY TRANSGRESSIVE SHOREFACE FACIES ASSOCIATION

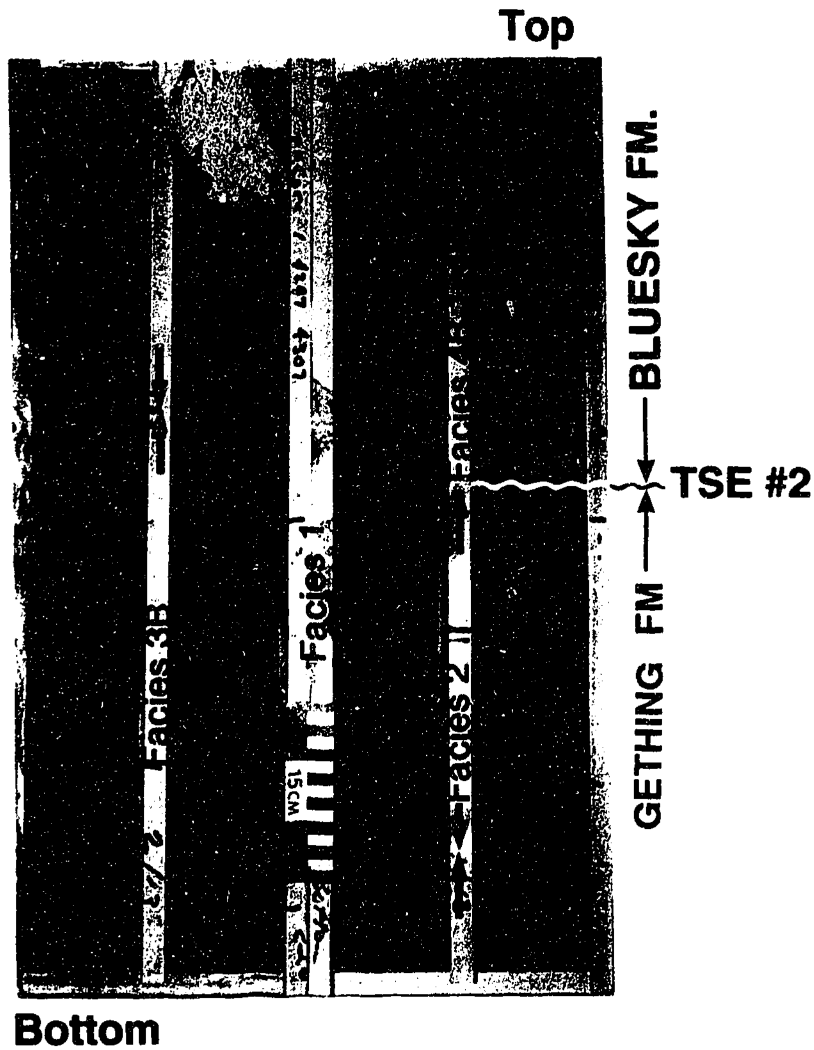
Two facies and two subfacies of the Bluesky Formation are interpreted to be of marine origin. The interpretation is based on the sedimentology, ichnology, and secondary diagenetic cements which are similar to features identified by Bourgois (1980), Nummedal and Swift (1987), Sha and de Boer (1991). The association is bounded above and below by wave ravinement surfaces.

5.4.1. TRANSGRESSIVE SHOREFACE FACIES ASSOCIATION

DESCRIPTION: This facies association is generally less than 4 m thick, displays both upward-fining and coarsening trends, and is underlain by a wave ravinement surface. The gamma-ray log response is a cylindrical, funnel-, or bell-shaped profile with an abrupt base (Fig. 25B). The basal contact is erosional and overlain by a transgressive lag (Facies 4B.1) of interformationally derived material up to 30 cm thick. The transgressive shoreface facies association is comprised of planar-bedded, matrix-supported conglomerate (Facies 4B.2), parallel-laminated sandstones, (Facies 3C), pebbly sandstones (Facies 3G), ripple-laminated sandstones (Facies 3B), intensely bioturbated sandstones (Facies 3F), or interbedded sandstones and mudstones having abundant wave ripple cross-laminations (Facies 2B) (Plate 14). The trace fossil assemblage includes *Palaeophycus, Terebellina, Helminthopsis, Chondrites, Teichichnus,* and *Skolithos.*

INTERPRETATION: This facies association is interpreted as a transgressive shoreface sandstone and conglomerate sequence. The coarse conglomerate unit (Facies 4B.1) is interpreted as seaward transport of sediment as a coarse lag associated with transgressive ravinement (Swift, 1968; Nummedal and Swift, 1987; Allen and Posamentier, 1991; Posamentier and Allen, 1993). The upward transition into muddy conglomerates, or pebbly sandstones and sandy mudstones suggest a progressive decrease in energy operating near the sediment water interface. The presence of dispersed pebbles within sandstones above the conglomeratic lag suggests a continued, though upward diminishing supply of coarse grained material during progressive deepening and continued transgression. Ripple cross-laminated to horizontal laminated sandstone suggest influence by both wave and tidal currents. These features are common in outer estuarine settings, such as the seaward margin of ebb-tidal delta deposits within the transgressive shoreface (Nummedal and Swift, 1987). Intensely bioturbated muddy sandstones infer low wave energy with infrequent storm events. Interbedded sandstones and mudstones infer moderate to high

Plate 14. Representative core photograph of the transgressive shoreface facies association. The basal contact is burrowed, with *Arenicolites* passively infilled with chert pebbles, extending downward into a Gething interdistributary bay-fill facies association. The contact is a *wave ravinement surface* (TSE #2) and is overlain by Bluesky transgressive shoreface conglomerate. Location: d-030-L/094-A-13; Depth 4247 ft-4257 ft.


Top
BLUESKY FM.
TSE #2
GETHING FM
Facies 3B
Facies 1
Facies 2
15CM
Bottom

energy storm dominated setting. Most sandstone beds are interpreted to reflect fairly distal storm event beds and their waning flow deposits in distal lower shoreface to offshore settings. The occurrences of siderite and glauconite infer slightly reducing conditions related to a relative sea-level rise. This facies association is capped by a wave ravinement surface that is associated with shoreline transgression.

5.5.0. BUCKINGHORSE FORMATION FACIES ASSOCIATION.

The facies described in section 4.3.0. have been grouped into a facies association that represent a vertical column of facies with gradational contacts between successive facies. Each association is bounded below by a wave ravinement surfaces, and internally punctuated by a marine flooding surface.

One distinct re-occurring transgressive shoreface facies association has been identified within the lower Buckinghorse Formation. The following subsections describe the depositional origin of this facies associations.

5.5.1. TRANSGRESSIVE OPEN MARINE SHELF FACIES ASSOCIATION

DESCRIPTION: This facies association abruptly fines upward, increasing in mudstone content upwards. The only well which cores this facies association is located at d-019-K/094-A-13 (Fig. 26). The facies association is greater than 15 m in thickness. The lower contact represents the third transgressive surface or wave ravinement surface and is overlain by a basal conglomeratic lag (Facies B2). This conglomeratic lag is sharply overlain by massive shaley mudstone

(Facies B1) containing dispersed chert pebbles (< 10%) within the low 10 cm of the facies. Marine trace fossils include *Helminthopsis* and *Planolites*. The association is punctuated by a marine flooding surface between the conglomeratic lag and shaley mudstones. Glauconite content ranges between 2 to 7 %, occuring as descrete, bright green, subangular to subrounded grains in a mudstone matrix.

Palynomorphs analysed from shaley mudstones of facies association 1 are characterized by common, generally poorly preserved microplankton, with relatively few terrestrial palynomorphs. Palynomorphs represented consist of common *Oligosphaeridium* ? *diastema*, *Chlamydophorella nyei*, Bisaccate pollen, Spores, *Cerebropollenites mesozoicus*, and rare to very rare *C. largissima*, *Palaeoperidinium cretaceum*, *Spiniferites ramosus*, *Florentinia* sp., cf. *Hexagonifera* sp., *Apteodinium* cf. *reticulatum*, *Cribroperidinium* sp., cf. *Meiouroganyaulax* sp., cf. *Spinidinium* sp., ? *Acanthaulax* sp., undifferentiated Dinoflagellates, *Lycopodiumsporites* sp., *Pterospermopsis* sp.

INTERPRETATION: During a relative sea level rise, high energy nearshore currents and storms will effectively transport material from the shoreface and redistribute the sediment seaward and landward. Coarse lag sediments suggest processes associated with surf-winnowing from shoaling waves during the advance of the transgressing Moosebar Sea. Swift (1968), based on studies of the Bay of Fundy, Canada, illustrated that shoreface ravinement surfaces are cut mainly by surf action along a narrow zone at the foot of the shoreface.

Komar (1975) suggests that the onshore-offshore shifts in sediment transport depends on the pattern of the asymmetrical orbital motions of shallow water waves. In this facies association, the transgressive lag is interpreted to have been deposited in the lower shoreface. In this case, facies 2 is interpreted to result from the last storm events (Burgeois and Leithold, 1984) reworking shelf deposits prior to the full marine incursion of the Moosbar Sea and emplacement of open shelf mudstones.

With continued deepening of the overlying water column, resulting from continued transgression of the Moosebar Sea, the shoreface continued to retreat. Through deepening, the effect of wave transport of sediments diminishes, and therefore, can no longer modify the texture of the sediment. The transition from a sandstone matrix to mudstone matrix suggest a waning of flow energy operating near the sediment water interface (Clifton, 1981; MacEachern *et al.*, 1992). At this point only very fine-grained sediments sizes are available to be deposited in lag material.

Massive shaley mudstone deposits overlie facies 2 with the contact between the two representing a marine flooding surface of the Moosebar Sea during full transgression and inundation of northeastern British Columbia. Facies 1 contains some minor evidence of bed load deposition, with sharp based siltstone and very fine-grained sandstone laminations interpreted to result from episodic, waning density flows as suggested by the normal graded, sharp-based siltstone layers. The dominant sedimentary processes infered for Facies 1 is deposition from suspension settling of clay sized particles below storm weather wave base. Trace fossils are interpreted as deposit-feeding annelids associated

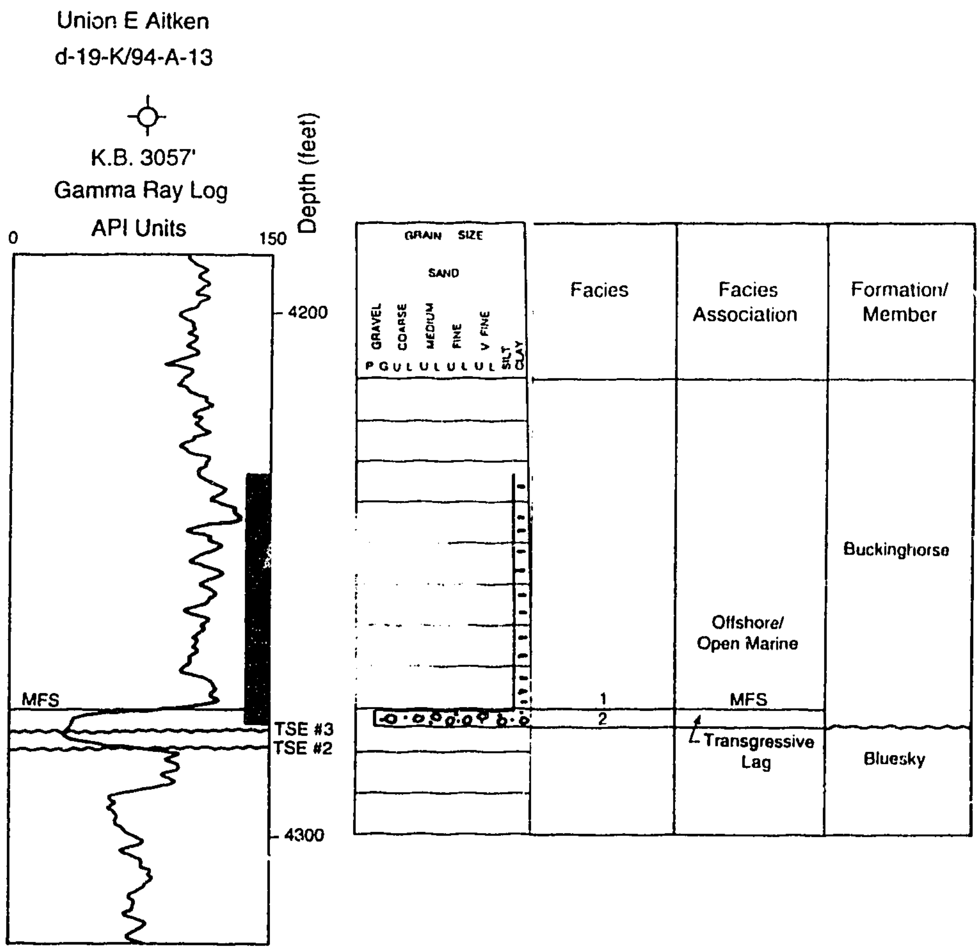


Figure 26. Transgressive shoreface-open marine shelf facies association. This facies association is bounded by a by a wave ravinement surface (TSE #3) below and punctuated by a marine flooding surface (MFS). Refer to Table 7 for key to lithology and symbols used in diagram.

with the distal *Cruziana* ichnofacies in lower shoreface to offshore environments (Frey and Pemberton, 1985; Pemberton *et al.*, 1992). Palynomorphs present suggest normal oxygen levels and salinity. The low abundance of terrestrial taxa indicates either a marine incursion or shelfal deposition at some distance from land. Facies 1 infers that the transgression of the Moosebar/ Wilrich Sea reached a sufficient water depth where by only fine sediment was able to accumulate on top of the transgressive lag. At this depth, either waves were unable to to modify the texture of the seafloor sediment significantly, or the shoreline retreated so far landward that only fine-grained sediment is available for deposition (Clifton, 1981).

6.0.0. SEQUENCE STRATIGRAPHIC FRAMEWORK

Until recently, the effects of accommodation associated with foreland basins had not been addressed, nor had the effects of tectonic control on individual sedimentary cycles and sedimentation patterns in these basin been fully considered within a sequence stratigraphic framework. Posamentier and Allen (1993a, b) and Devlin *et al.* (1993) have addressed the response of relative sea level to flexural response of the foreland basin to periods of thrusting and tectonic quiescence. The models developed in these studies are incorporated in the development of a sequence stratigraphic framework for the Lower Cretaceous Bluesky Formation, and consider the effects of tectonic controls on cycles of deposition and sedimentation patterns within the study.

6.1.0. SIGNIFICANT SEQUENCE STRATIGRAPHIC SURFACES

It is likely that the transgressive-regressive cycles of the early Cretaceous were strongly influenced by both eustasy and tectonics, both of which were controlling forces (Kauffman, 1977, 1984; Caldwell, 1984; Stott; 1984). In addition, in tectonically active areas, the ages of sequence boundaries when dated at the minimum hiatus at their correlative conformity produce a better match to the ages of the eustatic or relative sea-level falls than does the tectonic event which produced them (Vail *et al.,* 1991). This implies that, although tectonism may enhance or subdue sequences and their systems tracts, it does not create them (Vail *et al.,* 1991). The basal sequence boundary in the Aitken Creek Field (Fig. 27) is expressed as an unconformity on the valley floor and is interpreted as a Type-1 sequence boundary. Incision occurred during a period of relative tecotonic quiescence in the adjacent orogenic belt. Fluvial incision and the creation of a Type-1 sequence boundary probably reflect sufficiently low subsidence rates.

The depositional sequence in the Aitken Creek Field is not a complete one since it lacks an upper bounding unconformity, which in the normal course of events would have developed during the next fall of relative sea level. The depositional sequence in which Bluesky Formation valley-fill sediments are deposited was initiated in latest Aptian-earliest Albian times and represents a high-frequency cycle of approximately fourth order (Vail *et al.*, 1991) within a Lower Cretaceous third-order transgression (Kauffman, 1977, 1984; Caldwell, 1984; Stott, 1984). Although an upper bounding unconformity and associated correlative conformity and highstand systems tract are not present, the depositional facies and facies associations are characteristic of a depositional sequence, as outlined by Van Wagoner *et al.* (1990).

In the thalweg of the Bluesky incised valley-fill at the Aitken Creek Field, a Type-1 sequence boundary is represented by late Aptian (Gething Formation equivalent) delta plain sediments overlain by a fluvial channel-fill facies association (Plate 15A). On the valley walls, the sequence boundary is overlain by estuarine channel/tidal channel-fill, abandoned estuarine channel/ point bar, and subtidal estuarine bay-fill facies associations (Fig. 27). On interfluve areas, the sequence boundary may reflect subaereal exposure, although erosion during the subsequent transgression of the Moosebar Sea may have removed any evidence for such exposure (*i.e.*, paleosols). This transgressive erosion produces ravinement surfaces (Swift, 1968) which can result in removal of tens of meters of sediment (e.g., Allen and Posamentier, 1993) during tidal ravinement and 10-20 meters (e.g., Demarest and Kraft, 1987) during wave ravinement (Plate 15B).

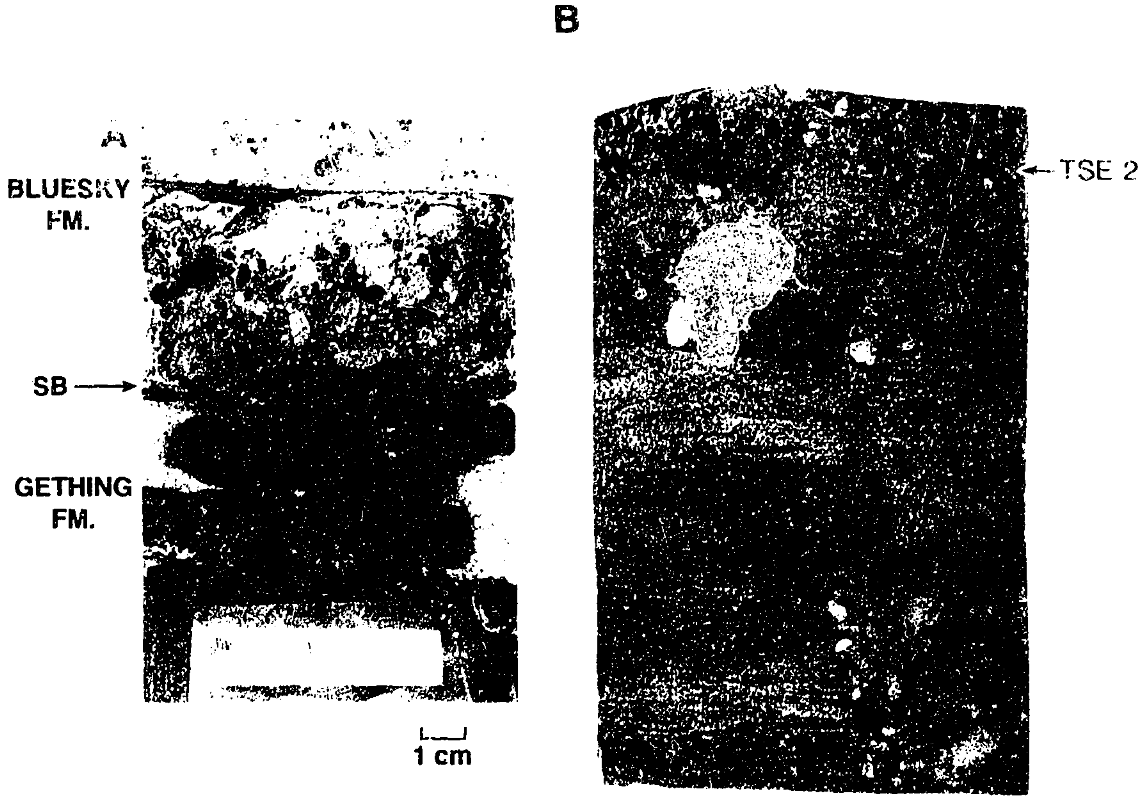
6.2.0. SYSTEMS TRACTS

Fluvial conglomerates and pebbly sandstones (fluvial channel-fill facies association) are interpreted as comprising the lowstand systems tract. The Aitken Creek incised valley was a zone of fluvial by-pass during the fall of relative sea-level. Assuming that the change in base level is large, river incision occurs and, therefore, seeks a lower equilibrium profile (Posamentier and James, 1993). A combination of slow base level lowering and tectonic uplift would rejuvenate the fluvial system and deliver large quantities of sediment to the shoreface (Schumm, 1993; Devlin *et al.*, 1993; Wood *et al.*, 1993). Basement involved tectonic movements will complicate the sedimentation patterns and contribute to the dramatic changes in the depositional style and paleogeography within the study area. An incising river tends towards the position of topographic minimum, which is commonly the site of maximum subsidence within a basin (Fig. 7). The course of the incising river can be deflected enroute to this position if the sedimentation rate more than compensates for subsidence or if the river is diverted by intrabasinal structures (Alexander and Leeder, 1987).

Plate 15.

A. Sequence boundary (SB) defined by the contact between polymictic and polymodal, matrix-supported, chert pebble conglomerate of the Bluesky Formation and coal of the Gething Formation. Location: d-025-L/094-A-13, 4410.9 ft.

B. Transgressive surface of erosion (TSE) , or ravinement surface, defined by the contact between the transgressive matrix-supported conglomerate lag and interbedded fine-grained sandstones and mudstones (Interdistributary bay-fill). The ravinement surface is characterized by the *Glossifungites* ichnofacies with *Arenicolites* (A) extending down below the transgressive surface of erosion (TSE). Location: d-030-L/094-A-13, 4248.1'.



B
A
BLUESKY FM.
SB
GETHING FM.
1 cm
TSE 2

Intrabasinal structures, such as grabens or thrust tips, can effectively divert and trap channels away from their optimal gravitational position in the basin (Alexander and Leeder, 1987; Leeder, 1993). When relative sea-level reached its lowest position and gradually began to rise, incision of the Aitken Creek valley was terminated and late lowstand deposits begin to accumulate within the walls of the incised valley (Fig. 27). Accommodation space for fluvially derived sediments is created in the form of localized low relief areas within the valley produced in response to paleotopography, basement-involved tectonism, or a combination of both. Structural features (Fig. 28) present are interpreted to have been initiated by reactivation of basement controlled normal faults (horsts and grabens) of the Hay River Fault zone, thrust faulting due to Columbian Orogenic activity, sediment loading, and foreland basin subsidence, or combinations of these listed. The Hay River Fault zone has strongly influenced the course of fluvial drainage systems within the Gething Formation. This control can be mapped to the Ring-Border area near the Alberta/ British Columbia border (D. Smith, pers. comm., 1994). The various tectonic events previously cited, and the resulting structural deformation to the upper Gething surface is interpreted to have disrupted the drainage course of the Aitken Creek incising river, deflected it around uplifted fault blocks and elevated topographic features on the upper Gething surface. The fluvial channel-fill facies association is preserved as a direct result of infilling of a structural low associated with the Hay River Fault zone, escaping reworking during the ensuing transgression by the Moosebar/ Wilrich Sea up the valley. This allowed fluvial sediments entrenched within the deepest locations of the tectonically induced valley to escape reworking or "canabalization" during the ensuing transgression of the Moosebar/ Wilrich Sea up the valley (Fig. 30; Plate 9).

During the rise of the Moosebar Sea the Aitken Creek incised valley was flooded and fluvial sedimentation in the valley ceased as salt water penetrated the fresh water system and the depositonal system evolved to an estuarine one. Estuarine facies are observed to onlap lowstand fluvial conglomerates in a paleolandward direction. An estuarine interpretation of these sediments is based on the abundance of tidally influenced bedding, biogenic structures, diversity of sedimentary facies, frequency of facies transitions and confinement of these facies to the incised valley (Fig. 29). These features are consistent with observations from modern mesotidal estuaries and the vertical facies associations they have generated (Frey and Howard, 1986). The base of the estuarine facies is a transgressive surface. Estuarine facies above this surface are interpreted as the transgressive systems tract deposited during passive infilling of the valleys. Although fluvial channel incision occurs during the fall of relative sea level, infilling of the incised valley occurs during latest lowstand and transgression, and thus most of the valley-fill deposits would be part of the transgressive systems tract (Allen and Posamentier, 1993).

Estuarine channel/ tidal channel-fill, abandoned estuarine channel/ point bar, subtidal estuarine bay-fill, and transgressive shoreface facies associations characterize the transgressive system tract within the study area (Fig. 21, 23, 25). Estuarine channel/ tidal channel-fill, abandoned estuarine channel/ point bar, and subtidal estuarine bay-fill facies associations are confined by the walls of the incised valley and comprise the transgressive systems tract in the Aitken Creek Field. Early transgressive deposits are confined to the incised valley, with a time lag before flooding of adjacent interfluve areas during base-level rise. As the transgression proceeds waves and tides truncate the upper valley-fill creating ravinement surfaces (Stamp, 1922; Swift, 1968; Posamentier and Allen, 1991). Transgressive shoreface sandstones and mudstones are deposited above interfluve areas, and within the valley overlie estuarine mouth facies comprised of tidal channel (inlet?) sandstones (Fig. 29).

6.3.0. Parasequence Stacking and Lateral Facies Variations, Aitken Creek Field

The transgressive systems tract of the lithostratigraphic Bluesky Formation consists of five retrogradational parasequences representing restricted to open marine facies deposited within the incised valley and on adjacent interfluve areas during transgression of the Moosebar/ Wilrich Sea in northeastern British Columbia.

The initial transgressive surface (ITS) is a marine flooding surface which defines the base of Parasequence BP 1 (Fig. 27 & 29), separating middle to upper estuarine facies associations above this surface from the lowstand fluvial channel-fill facies association below. This surface is interpreted as having been formed by up-stream migration of the bayline during flooding of the valley and is characterized by onlapping transgressive estuarine facies. On the valley walls, the initial transgressive surface merges with the sequence boundary, separating younger Bluesky transgressive estuarine facies from Gething delta plain facies (Fig. 34B).

Parasequence BP 1 is confined within the walls of the WSW-NNE trending incised valley, averaging approximately 1.5 km in width (Fig. 32). Local expansion and widening of parasequence BP 1 occurs over fluvial conglomerates in the Aitken Creek Field (up to 4.0 km in width). The widening of a incised valley over grabens is expected to occur with more frequency along the various incised valleys delineated in the study area. However, the recognition of valley widening is constrained by the data available. To recognize the widening of incised valley systems over basement grabens, the well control present in the Aitken Creek Field is required for such fields as Nig Creek (6.0 km northwest of Aitken Creek) and Pinto (12.0 km southeast of Aitken Creek). Additional well data may be obtained in the future by step-out drilling of Bluesky discoveries in these fields and potentially delineate this feature. Seismic data across the study area would define basement horst and graben structures, outlining potential structural sag to the Gething/Bluesky top and, thus, infer the depositional characteristics of the Bluesky Formation present in the Aitken Creek Field. Parasequence BP 1 ranges between 5.0 and 14.0 m thick, with local thickening observed on the cutbanks of estuarine channels. Active estuarine channel sandstones are laterally replaced by point bar sandstones and mudstones and abandoned channel silty mudstones, reflecting abandoment of the meandering estuarine channel system. Abandoned channel plugs are estimated to be up to 800 m wide. A neck cut-off is interpreted to be located

Figure 31. Schematic five stage sequence stratigraphic diagram illustrating formation of an incised valley-fill sequence in the Bluesky Formation, Aitken Creek Field, during initial fall and rise of relative sea level. A) (late highstand to early lowstand): widespread fluvial erosion occurs during initial fall of sea level. B) (lowstand): valley incision occurs in areas where sea level falls rapidly. C) (transgressive systems tract): incised valley becomes filled with upper to middle estuarine sediments as sea level rises.

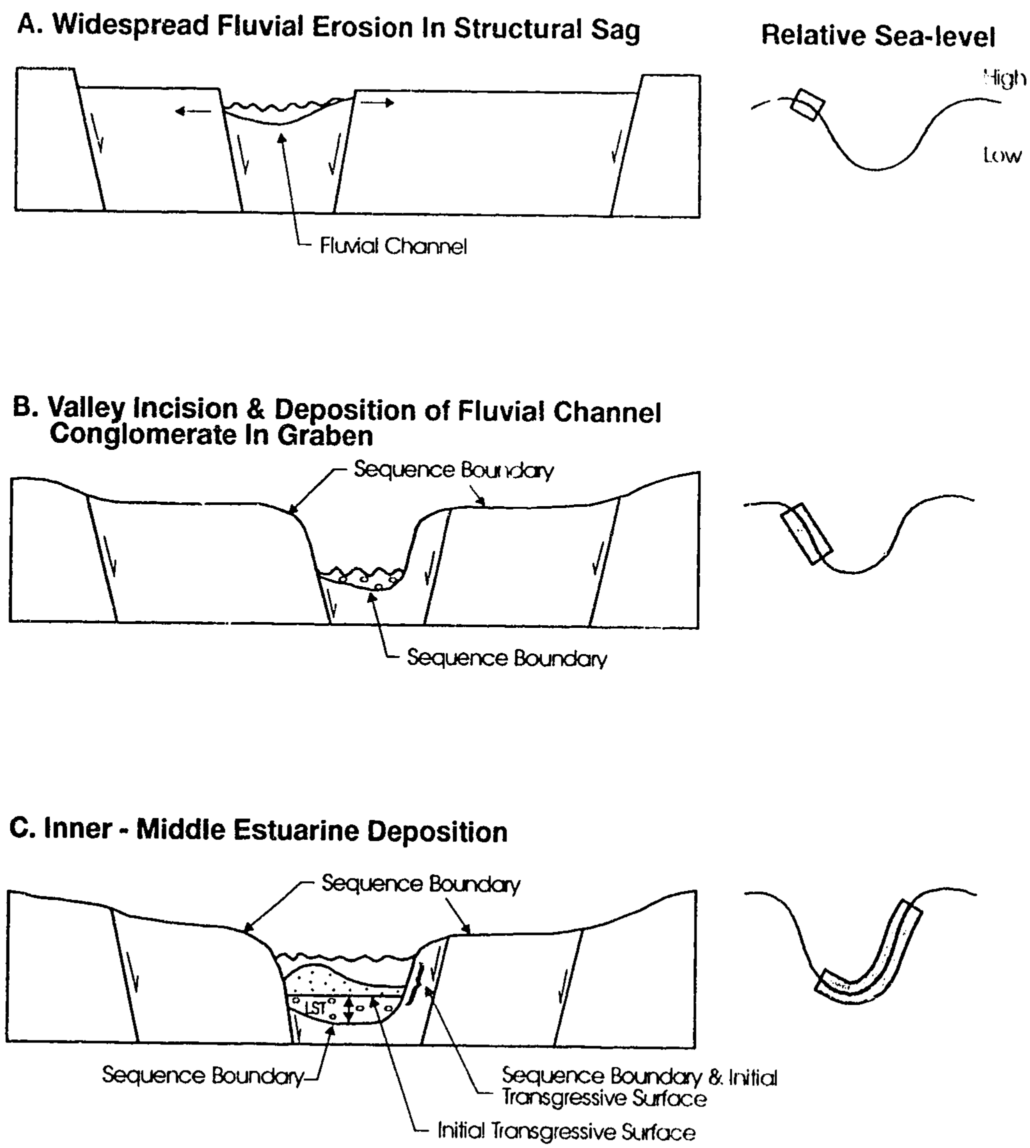
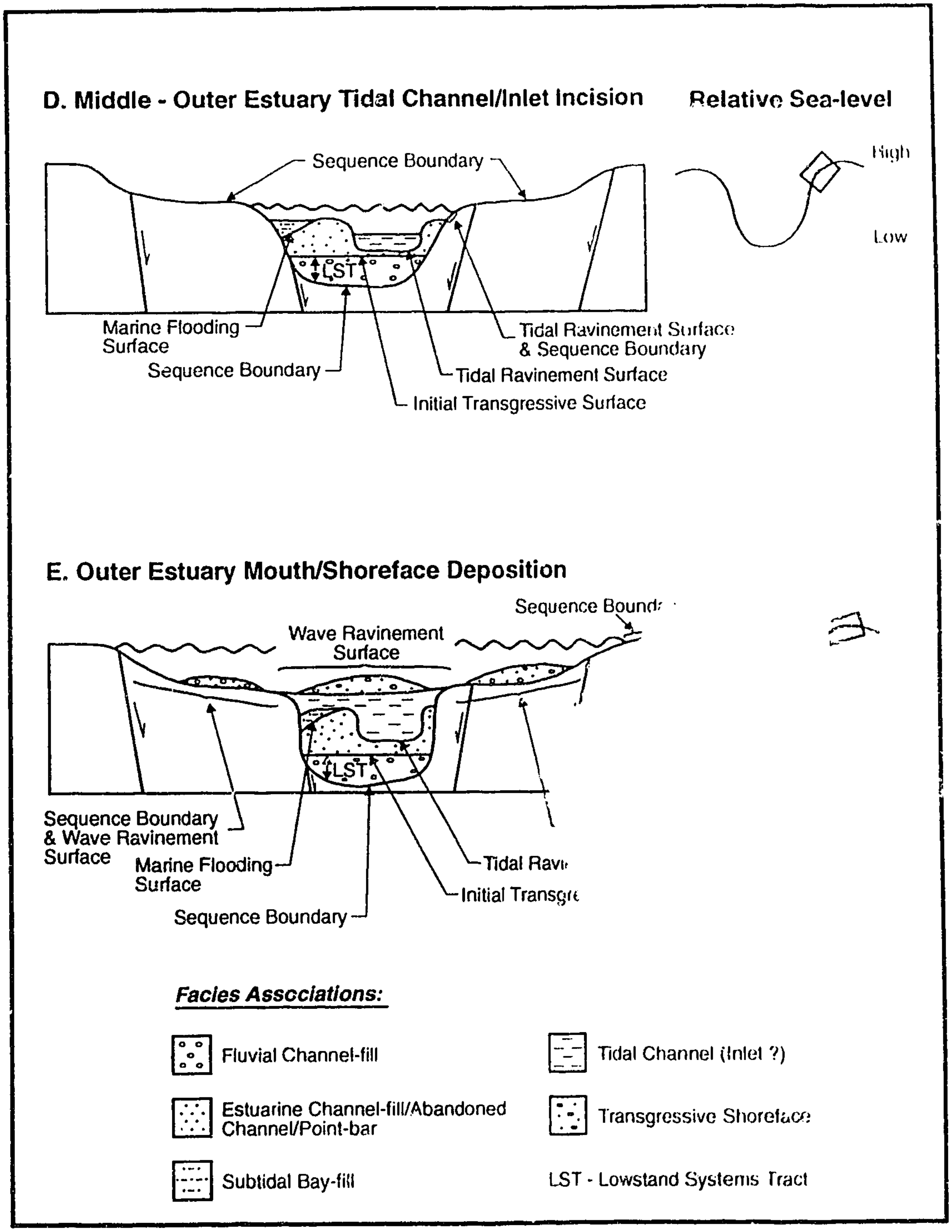

A. Widespread Fluvial Erosion In Structural Sag
Relative Sea-level
High
Low
Fluvial Channel
B. Valley Incision & Deposition of Fluvial Channel Conglomerate In Graben
Sequence Boundary
Sequence Boundary
C. Inner - Middle Estuarine Deposition
Sequence Boundary
LST
Sequence Boundary
Sequence Boundary & Initial Transgressive Surface
Initial Transgressive Surface

Figure 31. D) (middle to late transgressive systems tract): lower estuary deposits scour into bay-fill and upper to middle estuarine deposits with continued sea level rise. E). (middle to late transgressive systems tract): with continued sea level rise, the Aitken Creek incised valley becomes completely filled and sedimentation spreads across adjacent interfluve areas, deposition occurs in broad, outer estuarine embayment.


D. Middle - Outer Estuary Tidal Channel/Inlet Incision
Relative Sea-level
Sequence Boundary
High
Low
LST
Marine Flooding Surface
Sequence Boundary
Tidal Ravinement Surface & Sequence Boundary
Tidal Ravinement Surface
Initial Transgressive Surface
E. Outer Estuary Mouth/Shoreface Deposition
Sequence Bound
Wave Ravinement Surface
LST
Sequence Boundary & Wave Ravinement Surface
Marine Flooding Surface
Sequence Boundary
Tidal Rav
Initial Transg
Facies Associations:
Fluvial Channel-fill
Tidal Channel (Inlet ?)
Estuarine Channel-fill/Abandoned Channel/Point-bar
Transgressive Shoreface
Subtidal Bay-fill
LST - Lowstand Systems Tract

paleogeographic to the north of the Aitken Creek Field (Fig. 32) in response to the channel trying to achieve hydraulic efficiency, thus, locally increasing its gradient. Based on estuarine models by Dalrymple *et al.* (1992), Parasequence BP 1 should be transitional upstream outside of the study area into fluvial channel-fills and downstream into subtidal estuarine bay-fill sediments.

A second marine flooding surface separates Parasequence BP 1, below the flooding surface, from Parasequence BP 2, above (Fig. 27 & 29). Parasequence BP 2 consists of the subtidal estuarine bay-fill facies association. On the valley walls, this marine flooding surface merges with the initial transgressive surface and the sequence boundary (Fig. 31C).

Regionally, Parasequence BP 2 is confined within the walls of WSW-NNE trending, incised valleys, averaging approximately 2.0 km in width (Fig. 33). Local "expansion and widening", inferring an increase in surface area, of Parasequence BP 2 occurs over fluvial and middle- to upper estuarine valley-fills in the Aitken Creek Field (up to 4.2 km in width). Parasequence BP 2 ranges between 4.0 and 7.0 m thick, thickening to the northeast where incised valleys from the Aitken Creek and Nig Creek areas converge into a single valley, approximately 13.2 km wide. Lateral facies variations within the estuarine bay-fill are highly variable and change rapidly over short distances. Shoal/ sand sheets (3.0 km x 2.5 km) are laterally transitional with bioturbated, muddy intershoal areas (up to 1.5 km wide) and tidal creek mudstone facies. East of Aitken Creek, towards the estuary mouth (unit C, NTS block 94-H-4 and unit K, NTS block 94-A-13), bay-fill deposits increase in sand content and are not as muddy as upstream deposits in the Aitken Creek area. Paleo-upstream and outside the study (to the west), Parasequence BP 2 is expected to become coarser grained, and gradational with upper estuary channel and point bar deposits.

In the Aitken Creek Field, Parasequence BP 2 is overlain by Parasequence BP 3, which consists of sandstones and mudstones interpreted as subtidal estuarine bay-fills. Parasequence BP 3 contains a higher sandstone content than Parasequence BP 2. The marine flooding surface between the two parasequences merges on the Aitken Creek valley walls with the marine flooding surface below Parasequence BP 2, the initial transgressive surface (ITS), and the sequence boundary (SB).

Regionally, Parasequence BP 3 is laterally discontinuous, and only preserved in isolated locations within the study area. Its poor presevation is due to erosion from tides and waves during tidal and shoreface ravinement and the formation of two transgressive surfaces of erosion (TSE #1 and TSE #2).

Parasequence BP 3 is overlain by Parasequence BP 4, and consists of estuarine channel-fill sandstones. These facies are interpreted as lower estuary tidal channel and tidal inlet deposits, based on gamma ray signatures, facies geometry, and stratigraphic position (Fig. 29 & 31D). Similar deposits have been identified in the modern by Tye and Moslow (1993). The flooding surface between the two parasequences is erosional and scours into Parasequences BP 1, BP 2 and BP 3 (Fig. 27 & 29). This erosional surface was generated by a series of northeast-southwest oriented tidal channels (inlets?) that migrated laterally possibly under the influence of longshore currents and landward during transgression of the Moosebar Sea. The erosional surface is therefore a tidal ravinement surface analogous to the tidal channel erosion produced during rising sea level in the Gironde Estuary (France) (Allen and Posamentier, 1991).

The main incising channel is 8 m thick and 2.3 km wide in the Aitken Creek Field, decreasing in thickness and increasing in witdth paleoseaward (Fig. 34). The fill is predominantly sandstone in the main northeast-southwest trending channel. Adjacent laterally-migrating tidal channels are interpreted to be finer grained and thinner, based on gamma ray log response. The fine grained nature of the tidal channels is interpreted as abandonment of the channel. Thinning of this parasequence basinward to the northeast is due to shoreface ravinement during transgression. The shoreface ravinement surface (TSE #2) truncates the tidal ravinement surface to the southwest in the area of the Aitken Creek Field.

The wave ravinement surface (TSE #2) immediately overlying estuarine valley-fill facies and interfluve areas is burrowed and represents an ichnologically demarcated erosion surface characterized by the *Glossifungites* ichnofacies (Plate 15B). This substrate-controlled ichnofacies develops because the exhumed surfaces are generated within marginal marine or marine environments, favoring colonization by organisms as the surface is cut, but prior to any significant deposition or deepening of the water column (MacEachern *et al.*, 1992). Lying lateral to the Aitken Creek incised valley, interfluve areas are characterized by a co-planar sequence boundary (SB) and wave ravinement surface (TSE #2). Where as within the Aitken Creek incised valley, the co-planar sequence boundary (SB) and wave ravinement surface (TSE #2), located on interfluve areas, is correlative with a wave ravinement surface (TSE #2) (Fig. 27, 29, & 31E). Sediments deposited above the wave ravinement surface are characterized by the transgressive shoreface facies and comprise Parasequence BP 5 (Plate 14, 15B). The lithology of these deposits is highly variable, and changes rapidly over short distances. For the most part, Parasequence BP 5 is coarse grained, but grades laterally into an intensely bioturbated muddy sandstone and coarsening- and fining upward interbedded sandstone and mudstone. This facies heterogeneity disrupts the continuity within potential reservoir quality coarse grained clastics within Parasequence BP 5. Local removal of Parasequence BP 5 occurs to the northwest, paleolandward of the Aitken Creek Field in response to a second wave ravinement surface (TSE #3) which erodes this parasequence in a paleolandward direction (to the southwest) during transgression (Fig. 35).

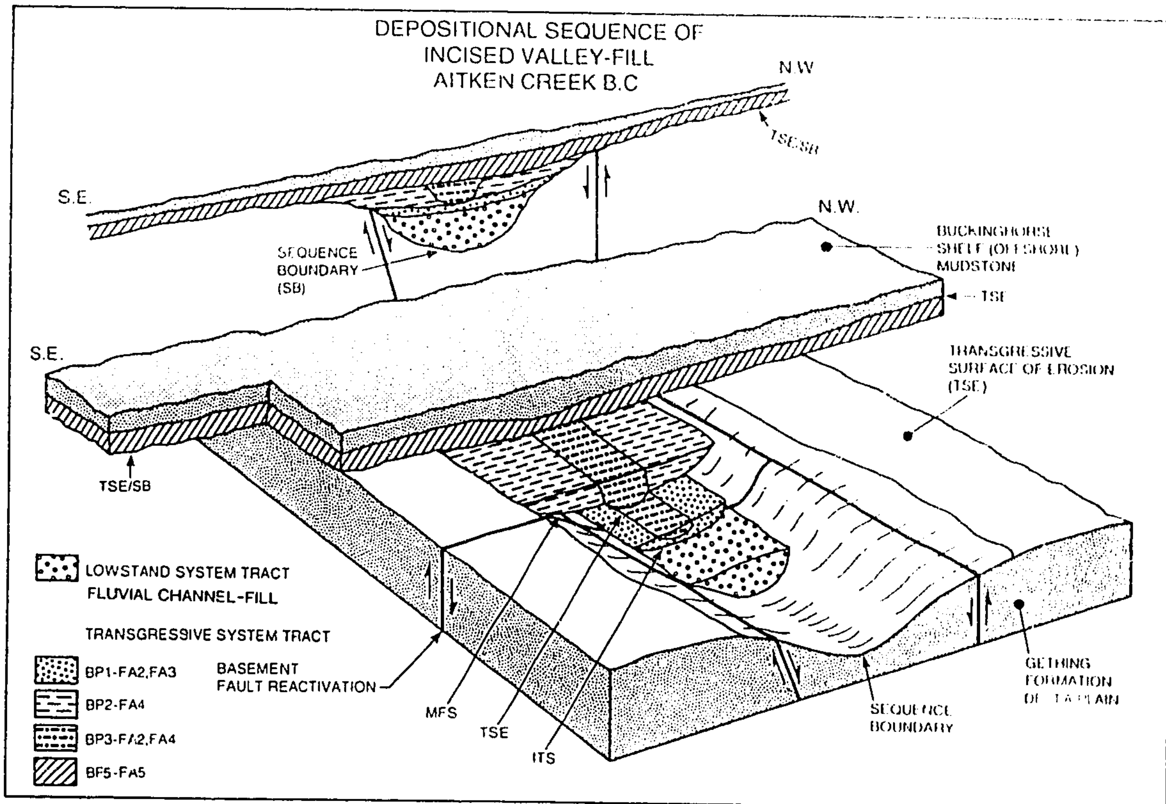
The final wave ravinement surface (TSE #3) is overlain by a thin matrix-supported conglomerate and represents the base of the Buckinghorse Formation (Fig. 27 & 29). This conglomerate is interpreted as a transgressive lag and is overlain by shelf mudstones. This lag is considered to represent Stelck's (1990) "homotaxial shallow bar facies" of the Wilrich Member. A similar wave ravinement surface and transgressive lag has been interpreted between the lower Wilrich Member contact with the Bluesky

Formation in the Karr area of west-central Alberta (Male, 1992). However, the correlative relationship between the wave ravinement surface in the Karr area to the wave ravinement surface (TSE #3) in the Aitken Creek Field still needs to be varified through regional stratigraphic correlation.

7.0.0. DEPOSITIONAL MODEL–AITKEN CREEK FIELD

The depositional model for the Bluesky Formation, Aitken Creek Field, includes a wide range of sedimentary environments that characterize an fluvial-estuarine valley-fill. Depositional environments of the valley-fill include a fluvial channel incised into delta plain sediments, active and abandoned estuarine channels with attached shoals, subtidal estuarine bay fills, tidal channels incising abandoned estuarine channels, subtidal estuarine bay fills, and a transgressive shoreface eroding interfluve and estuarine mouth deposits (Fig. 36).

Palynologic analyses indicate that valley-fill sediments are early Albian in age (Table 2). Prior to early Albian flooding of the incised valley, fining-upward facies associations of clast- and matrix-supported conglomerate and pebbly sandstone were deposited in the thalweg of the valley (Plate 15A). The preserved record of fluvial sedimentation in the valley during lowstand or transgression is a section equivalent in thickness to that of a single fluvial channel (Fig 20A; Plate 9). The channel occupies the deepest valley incision in an area of low relief on top of the Gething Formation (oriented WSW to ENE) produced in response to: a) paleotopography, b) reactivation of normal faults associated with the Hay River Fault Zone, or c) a combination of both (Plate 15). Movements on various basement controlled faults has occurred throughout the Triassic up to the Middle Cretaceous (interpretation by the author based on the correlation of flooding surfaces within the Gething Formation, isopach thickness variation of formations



(*Modified from Weimer,1992)

FA2 - ESTUARINE CHANNEL-FILL

FA3 - ABANDONED ESTUARINE CHANNEL/ POINT BAR

FA4 - SUBTIDAL ESTUARINE BAY-FILL

FA5 - TRANSGRESSIVE SHOREFACE

Figure 36. Schematic block diagram illustrating key markers used to define Bluesky valley-fill deposits within a sequence stratigraphic framework (modified from Weimer, 1992).

(i.e. Nordegg Formation, Gething Formation), and confidential seismic data from Mobil Oil Canada 10 to 20 km west and north of Aitken Creek - lines 85-T-539, 91-T-1380, 91-T-1403, and 91-T-1415). The result of basement-involved tectonic movements caused the eroding fluvial channel to seek a lower equilibrium profile. It is difficult to confirm the style of the channel system within the study area. Not enough of the channel system has been studied to infer a subregional drainage style or sinuosity.

Estuarine facies overlying lowstand fluvial facies indicate that the sea-level rise was sufficiently rapid that the increased accommodation space was greater than the fluvial influx of sediment. Transgressive estuarine facies associations represented by estuarine channels (Fig. 21), abandoned estuarine channels (Fig. 23), and subtidal estuarine bay-fills (Fig. 25A) represent the transition from a fluvial to an estuarine valley during transgression of the Moosebar Sea. In vertical section, this facies transition is abrupt and corresponds to a marine (*i.e.*, tidal) flooding surface that migrated landward over lowstand fluvial channel deposits. Within the Aitken Creek Field, this surface is locally erosional, but does not appear to scour deeply into underlying deposits.

The tidal regime within the Cretaceous Interior seaway is poorly understood. Klein and Ryer (1978) concluded that ancient shallow epeiric seas, including the Cretaceous seaway, were tidally dominated and the effects of tides and tidal circulation patterns have largely been overlooked by geologists. Klein and Ryer's (1978) conclusions of relatively strong tidal currents is based on the assumptions that regular tidal flushing of a semi-enclosed basin (lagoon, estuary and shallow marine environments) is necessary in order to maintain the established benthic invertebrate populations present in these deposits. Additional evidence was based on the numerous examples of primary physical sedimentary structures displaying distintiive characteristics features of tidally influenced environments (Nio and Yang, 1991) and growth cycles present within microstructure of bivalve shells which record neap-spring tidal fluctuations. Tillman and Martinsen (1985) suggest that the tides varied between micro- to low mesotidal ranges as inferred from Upper Cretaceous outcrops within the epicontinental sea.

The sedimentary features observed within the Bluesky Formation are interpreted to have been deposited under mesotidal influence and are comparable to described facies in modern mesotidal estuaries which include Willapa Bay, Washington (Clifton and Phillips, 1980; Clifton, 1982; Smith, 1988) and Daule and Babahovo Rivers, Ecuador (Smith, 1988). The presence of tidally-influenced sedimentary structures infer amplification of the tide entering the incised valley during transgression of the Moosebar/ Wilrich sea and creation of a local mesotidal regime within the microtidal epicontinental seaway.

During the early Albian ("Moosebar/ Wilrich") transgression, estuary mouth sandstones and pebbly sandstones migrated landward up the incised valley estuary (Fig. 36). Preserved evidence for this migration in the Aitken Creek Field includes a tidal channel in Well d-024-L/094-A-13 in cross-section *M-M'* (Figure 27). The tidal channel eroded in to abandoned estuarine channel mudstones and subtidal estuarine bay-fill facies and is overlain by transgressive shoreface facies. The base of the tidal channel forms part of a major transgressive erosional surface, termed the *tidal ravinement surface* (Fig. 36) (Allen and Posamentier, 1993). Tidal inlet migration within the study is comparable to the modern Bolivar Roads tidal inlet (east Texas Gulf Coast), migrating in response to longshore currents (Fig. 37). When the migrating Bolivar Roads tidal inlet encountered more resistant Pleistocene sediments along the western edge of the Trinity River incised valley, it migrated southward, along the valley edge (Fernando et al., 1993). The landward translation of shoreface facies across the flooded estuarine valley formed a *wave ravinement surface.* (Swift, 1968) The tidal and wave ravinement surfaces are laterally correlatable throughout the upper section of the Bluesky Formation in the Aiken Creek Field and infer a complex history of transgression, culminating in the deposition of the open marine (*i.e.,* offshore) shales of the Buckinghorse Formation (Fig. 36).

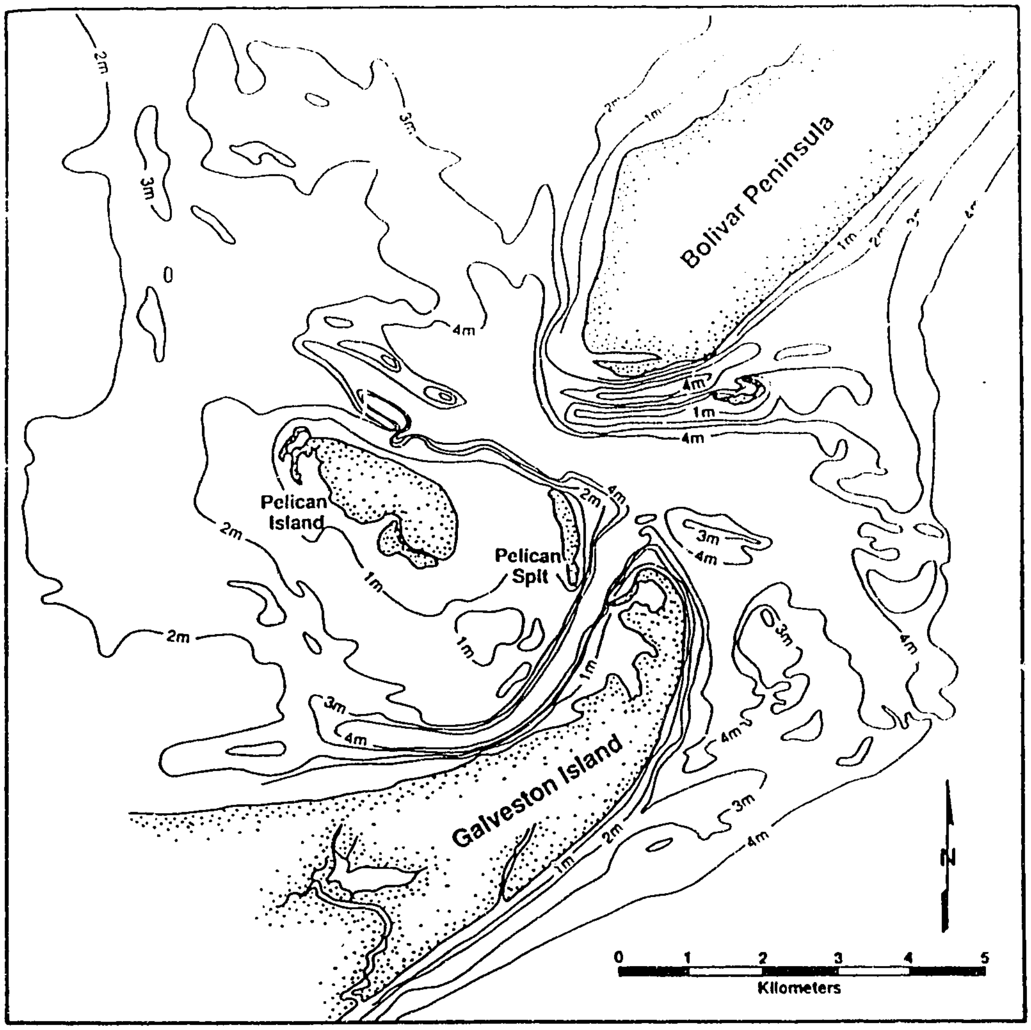


Figure 37. Isopach map of Bolivar Roads tidal inlet. Note the similarity between the laterally migrating tidal inlet channel and the features in figure 33, Bluesky Parasequence 4 (modified from Fernando *et al.*, 1993).

8.0.0. DISCUSSION

A series of isopach maps of the lowstand systems tract (Fig. 30) and transgressive systems tract parasequences (Fig. 32, 33, 34, 35) in the study area contain several interpreted incised valley systems. Several concerns are raised involving the timing and emplacement of interpreted incised valleys to the north (Nig Creek) and south (Pinto) of the Aitken Creek Field and, therefore, impact the regional interpretation of the Bluesky Formation in northeastern British Columbia. The Aitken Creek Field incised valley was produced during a relative fall in sea level, responding to local or regional tectonism. Even though northeastern British Columbia was experiencing a third order transgression during Aptian-Albian time (Gibson, 1992), the initial surface of deposition must have been rising at a faster rate than that of sea level. Seismic reflection data shows numerous early Cretaceous thrust faults to the west of Aitken Creek and interpreted to result from Cordilleran compressional events. Aptian tectonism (Stott, 1972; Jeletzky, 1978) is interpreted to have initiated the base level changes necessary to produce the fourth-order fall in relative sea level.

Regionally, the study area is located within a structural sag produced by syndepositional movement of basement blocks or faults (Interpretation of the author from proprietory seismic data 20 to 30 km west of Aitken Creek, Mobil Oil Canada data, 1994). The structural sag is approximately 30 to 50 km in width, oriented southwest to northeast, and is parallel to the Hay River Fault zone (Fig. 8). The trend of the Early Albian Bluesky fluvial systems may be controlled by this structural sag due to increased accommodation space (Fig.

38). During transgression, estuarine deposition may be localized within the downwarp as a function of the greater accommodation space. Areas flanking the downwarp show Gething deltaic sediments overlain by thin Bluesky transgressive lag conglomerates and pebbly sandstones, and/ or capped by Buckinghorse shelf mudstones (D. Smith, pers. commun., 1994).

It is difficult to determine from the data set with any degree of confidence if the interpreted incised valleys within the Aitken Creek study area resulted contemporaneously during the fall in relative sea level or represent a multicycled system similar to Gibson (1992) for sea level reversal in similar age sequences. Gibson (1992) infers two fourth-order Late Aptian-Early Albian lowstand events within the third order Moosebar transgression in Gething Formation deposits. Fourth-order sequence boundaries are inferred at the top of the Gaylard Member (Aitken Creek Field) and top of the Chamberlain Member, south of the Sukunka-Pine River area. Chamberlain Member deltaic sediments are not deposited in the Aitken Creek area, but downlap Bullmoose Member shales in the area of the Dawson Creek Graben Complex (D. Smith, pers. commun., 1994). The Dawson Creek Graben Complex created too much available accommodation space for Chamberlain Member sediments to infill and, therefore, did not prograde into the Aitken Creek area. In addition, there is no evidence from core data of a second sequence boundary within the Aiken Creek Field (i.e. basinward shift in facies, erosion and truncation of sequence stratigraphic surfaces). Although highly unlikely, a Chamberlain Member age sequence boundary may be present within the Aitken Creek study area, however the data available will neither confirm or deny its presence at this time.

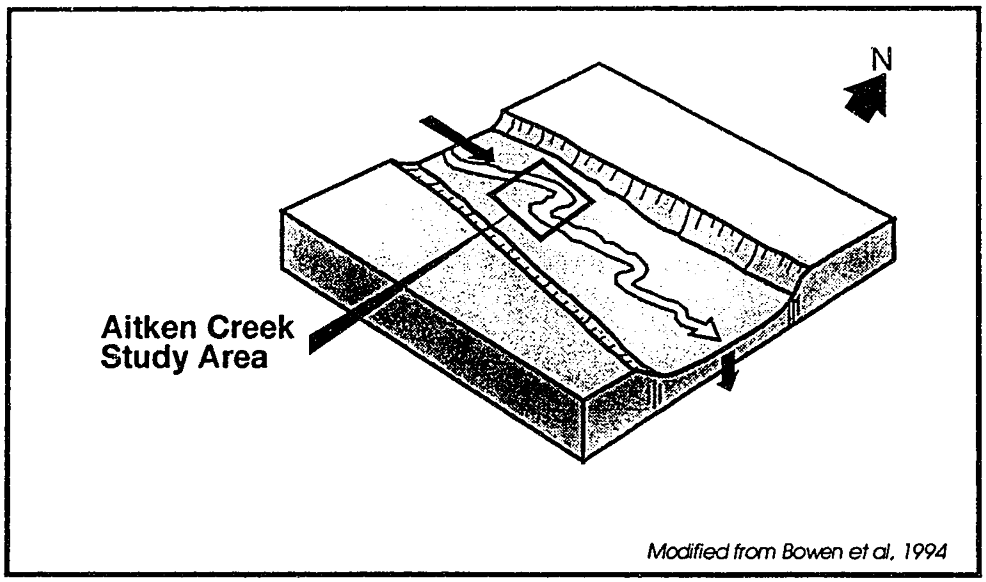


Figure 38. Fluvial and estuarine sediments may develop along the axes of structural sags. Such tectonically controlled systems may be developed locally above basement fault blocks of the Hay River Fault zone. The position of the Aitken Creek study area relative to the structural sag identified from structural mapping and seismic data is indicated on the diagram (Modified from Bowen *et al.*, 1994).

The incised valley systems in the Aitken Creek study area may represent a series of terrace channel deposits, similar to stratigraphic relationships observed for the upper Colorado valley (Fig. 39) (Blum, 1994), representing protracted incision during the Late Aptian-Early Albian relative fall in sea level. The sequence boundary occuring at the base of incised channels in Nig Creek (6 km N.W. of Aitken Creek) and Pinto (12 km S.E. of Aitken Creek) occurs at the same stratigraphic level as the intial transgressive surface within the Aitken Creek Field. The sequence boundary within the Aitken Creek Field occurs at a lower stratigraphic level as compared to these valleys to the north and south, and may represent a protracted trend of valley deepening in response to basement fault movements and Cordilleran compressional tectonism. The absence of interfluve deposits may be the result of removal during incision of various allostratigraphic units or no data available to confirm the deposition of these sediments.

The interpreted channel system north (Nig Creek) and south (Pinto) of Aitken Creek is clearly absent of a developed lowstand fluvial root system. In order to call these interpreted channels incised valleys, is it an absolute requirement that all incised valleys contain a preserved lowstand fluvial root system below transgressive estuarine valley fill deposits? Aitken Creek is considered unique, in that the lowstand systems tract is remarkably well preserved, and represented by fluvial channel-fill conglomerate above a graben system. The grabens acted as local accommodation space available for deposition of fluvial conglomerate from the bedload dominated incising channel. During the following transgression of the Moosebar Sea, upper sections of fluvial derived sediments

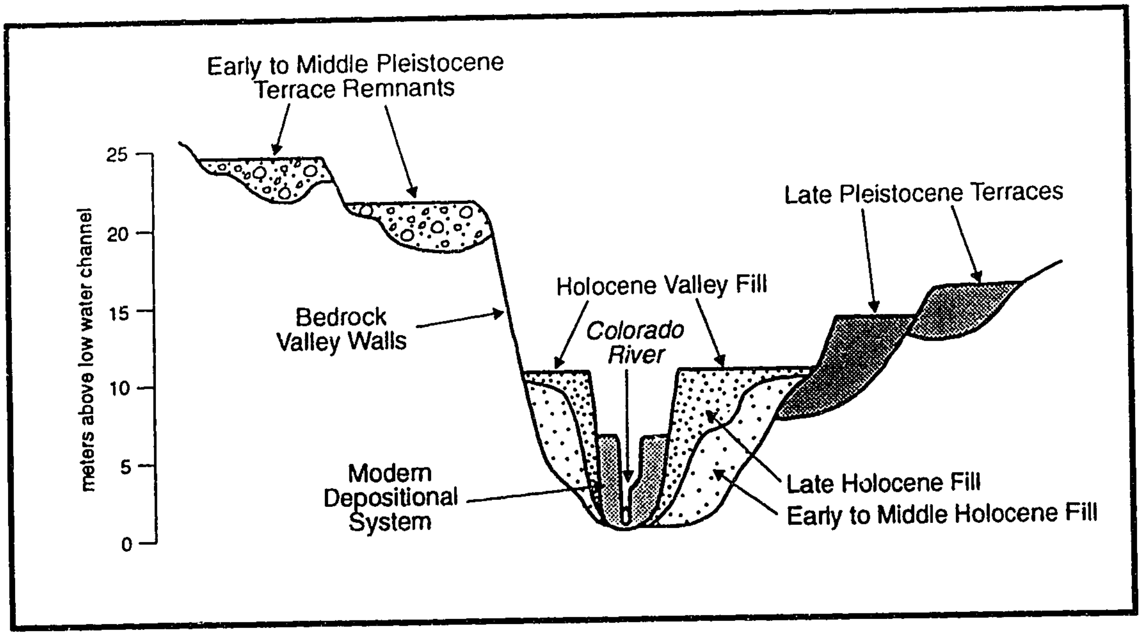


Figure 39. Schematic cross section of the upper Colorado valley near the confluence of the upper Colorado and Concho rivers, illustrating common geomorphic and stratigraphic relationships between different allostratigraphic units. Although the dynamics of the incised valley systems are widely different, the Aitken Creek incised valley may have a similar cross-sectional stratigraphic relationship as observed in the Colorado and Concho river cross-section (modified from Blum, 1994).

within the Aitken Creek incised valley were re-worked in to riverine-estuarine deposits. Only those sediments that were deposited within grabens, the deepest part of the incised valley, escaped re-working during transgression. Comparison with sequence stratigraphic models for estuarine deposits (Dalrymple *et al.*, 1992; Allen and Posamentier, 1992), each of the estuarine valley-fill sequences to the north (Nig Creek) and south (Pinto) of the Aitken Creek Field consists of dominantly transgressive systems tract deposits and clearly absent in developed lowstand systems tract deposits. The lack of lowstand fluvial channel-fills in Bluesky Formation incised valleys may be attributed to by-pass of fluvial sediment to lowstand deltas located further basinward (Allen and Posamentier, 1993) or to erosional removal and re-working of fluvial lowstand deposits by estuarine tidal scour during subsequent transgression (Dalrymple *et al.*, 1992; Reinson, 1992). A similar interpretation has been used for the Viking Formation (Pattison and Walker, 1994) and Glauconitic member (Wood, 1994) in Alberta to explain the absence of lowstand systems tract deposits within incised valleys.

The incised valley-fill system interpreted for the Aitken Creek study area may represent a system of dendritic tributaries developed during relative lowstand in sea level, analogous to the Morrow Sandstone, southeastern Colorado (Fig. 40) (Bowen *et al.*, 1994). If this is the case, then the absence of coarse-grained fluvial clastics may have occurred through the following events. The Bluesky fluvially incised channels in the Aitken Creek study area are confined by the walls of a large structural sag associated with basement horsts and grabens. The headward erosion of tributaries during periods of sea level lowstand may have formed dendritic tributaries, which further dissected the exposed lowstand relief surface. During late lowstand to early transgression of the Moosebar Sea, thick fluvial conglomerate deposits are interpreted to have accumulated along major valley axes within grabens due to the increased local accommodation space and preservation potential from re-working by tidal scour during transgression.

During transgression and infilling of Morrow Sandstone valleys, reservoir sands were deposited alon the valley axes of major trunk streams. Morrow valley-fill coarse-grained clastics were not deposited in the minor tributaries nor in the areas flanking the valleys (Bowen *et al.*, 1994). The absence of fluvial root systems to Bluesky incised valleys north and south of the Aitken Creek Field infers the possibility that these channels may represent tributaries of a major incised valley, with the Aitken Creek Field situated in the major valley axes. Intervalley sediments were not deposited in areas flanking Bluesky incised valleys during Parasequence BP 1 and BP 2. The first evidence of intervalley deposition is during Parasequence BP 3. Middle to upper estuarine bay-fill deposits began to encroach upon the Aitken Creek Field from northeast to southwest, inundating interfluve areas that were previously exposed.

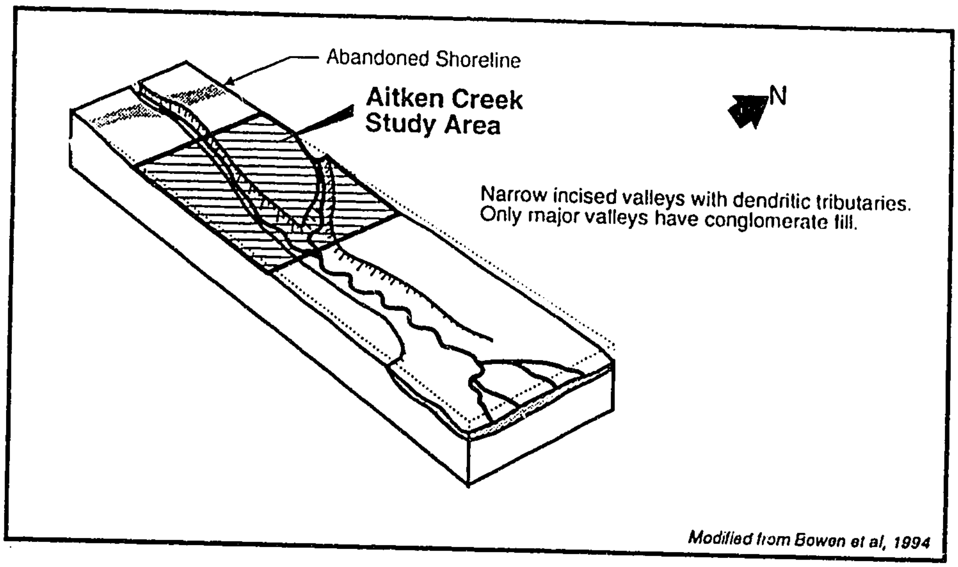


Figure 40. Aitken Creek incised valley systems may have evolved similarly to Morrow Sandstone incised valley-fill systems in southeastern Colorado. Small fluvial systems incised in to a low gradient surface during relative falling sea level. A system of dendritic tributaries developed during relative lowstand in sea level. Sands were deposited along Morrow Sandstone major valley axes during transgression (Modified from Bowen *et al.*, 1994).

9.0.0. PETROLEUM GEOLOGY

Hydrocarbon reservoir facies in the Bluesky Formation within the study area include fluvial and estuarine channel-fills, and transgressive shoreface chert sublitharenite to litharenite conglomerates and pebbly litharenites. The main oil and natural gas producing reservoirs at Aitken Creek are fluvial channel-fill, estuarine channel, tidal channel (inlet ?), and subtidal bay-fill shoals. Limited natural gas potential occurs in transgressive shoreface deposits. Natural gas production is obtained from estuarine channel sandstones, pebbly sandstones and matrix-supported conglomerates in wells from Nig Creek, approximately 6.0 km northwest of Aitken Creek.

9.1.0. RESERVOIR QUALITY

The primary controls on reservoir quality in the Aitken Creek Field are primary sedimentological characteristics (i.e. sand/mud ratio's, size and sorting of sediment grains, conglomerate and sandstone bed continuity) and burial diagenesis. A number of burial diagenetic changes have occurred within valley-fill sediments of the Aitken Creek Field profoundly affecting the reservoir quality of sandstone and conglomerates.

Facies 1, 2A, 2B, and 5 (Table 5) are found above the main reservoir trend and are non-reservoir facies due to the high mudstone, or carbonaceous, content and relatively thin, fine-grained sandstone beds. Due to the fine-grain size of the sandstones, primary pore spaces are small allowing the primary porosity and/or permeability to be occluded. Vertical continuity of sandstones in facies 2A and 2B is poor due to interbedded mudstone as laminae and beds. The horizontal continuity of these facies is expected to be good since the mudstone beds and laminae are horizontal in cores. These facies may, however, also serve as potential hydrocarbon seals.

Facies 3A sandstones are fine- to medium grained, with few detritus clays. In the fine-grain size range, primary pore spaces are small allowing the primary porosity and/or permeability to become reduced due the packing arrangement of the grains or diagenic cementation. The vertical continuity of the sands in facies 3A is lower than in Facies 3B, 3C, and 3F; with tidal bundles and mud drapes less than 5 cm apart. Bioturbation does not significantly affect permeability in Facies 3A, 3B, 3C, and 3F. Mudstone intraclasts or chert pebbles found within any one of these facies are interpreted to have no effect on primary reservoir quality. Horizontal continuity of sands in Facies 3B and 3C is greater than Facies 3A and 3D, as the latter sands are more aerially restricted compared to Facies 3B and 3C, and tidal couplets may become tangential to bedding contacts. Although the sedimentological characteristics of Facies 3B and 3C are indicative of good reservoir quality sandstone, they are relatively thin (less than 2.0 m thick). Thus, their vertical continuity is questionable.

Facies 3E sandstones have considerably higher mudstone content due to the intense reworking of this facies by deposit- and suspension-feeding organisms, and are thus not reservoir facies.

Facies 4A and 4B consist of chert pebble sublitharenite to litharenite conglomerate with few detrital clays, and represent the main conglomeratic reservoir facies within the Aitken Creek Field. The coarseness of the pore network allows primary porosity and/ or permeability to become reduced, but not occluded. Vertical continuity is the greatest in Facies 4A (Avg. Porosity: 12%; Avg. Perm.: 2.0 D), as this facies consists of clast-supported, open to closed framework, horizontal bedded, trough and planar tabular cross-bedded conglomerates in excess of 15 m thick. The occurrence of Facies 4B interbedded with Facies 4A may reduce, or impede, the vertical continuity. The horizontal continuity of Facies 4A is good, but as stated earlier, may be impeded by Facies 4B. However, the sedimentological characteristics of these facies are indicative of excellent reservoir quality.

Diagenetic changes have significantly affected the reservoir properties of sandstones and conglomerates in the Aitken Creek Field. Primary porosity has been significantly reduced in conglomerate but not to the extent as observed in sandstones. Quartz overgrowths are predominantly responsible for the reduction of primary porosity. Possible sources for silica in solution in the Aitken Creek Field are: 1) pressure solution of detitial grains due to compaction; 2) an unstable phase of detrital chert reverting to silica in solution due to changes in pressure and temperature during burial; 3) silica-rich solution waters flowing through sandstones and conglomerates from surrounding mudstones; and 4) silica-charged meteoric waters during early burial of the valley fill sequence. Sandstones are prone to reduction in porosity because of their finer-pore network and reduced thickness compared to fluvial chert (radiolarian and opal) pebble conglomerates experiencing the same discharge of silica-rich solution per unit volume of sediment.

Siderite cement forms along detrital grain boundaries, representing a later diagenetic phase than quartz overgrowths in the reservoir. Although not as common as quartz overgrowth cementation, siderite occurs at any depth within incised valley-fill deposits. There is a strong correlation between detrital organic material, carbonaceous sedimentary rock fragments and the preferential occurerence of siderite cement.

The principal origin of Blueksy Formation porosity in the Aitken Creek Field is primary, preserved during an early compaction and quartz cementation phase. However, secondary porosity within the main reservoir facies of the Aitken Creek Field may have been induced by pressure dissolution of detrital chert and through fracturing during fault reactivation involving basement structures associated with the Hay River Fault zone. However, the amount of secondary porosity created by these mechanisms in the reservoir is uncertain.

9.2.0. Petrophysical Properties of Reservoir Facies Associations

Graphic representation of whole core analysis measurements (Appendix B) for each facies association are shown in figures 41, 42, 43, & 44. Average porosity values for the fluvial channel-fill facies association are highest

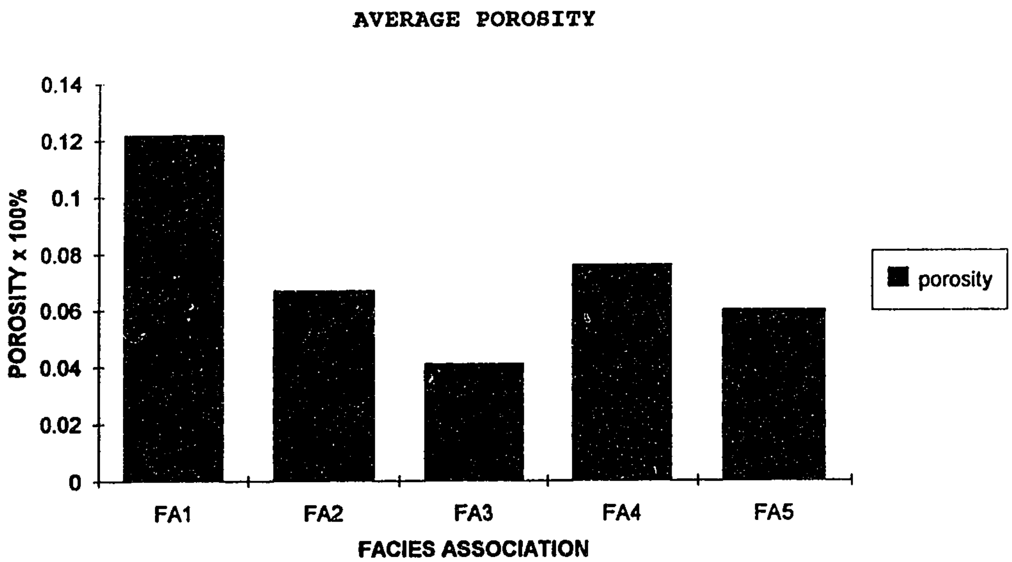


Figure 41. Histogram of average porosity values for facies associations identified within the Aitken Creek Field. Fluvial channel-fill conglomerates (FA 1) show the highest average porosity values. (FA 2: estuarine channel/ tidal channel-fill; FA 3: abandoned estuarine channel/ point bars; FA 4: subtidal estuarine bay-fill; FA 5: transgressive shoreface) N= 23.

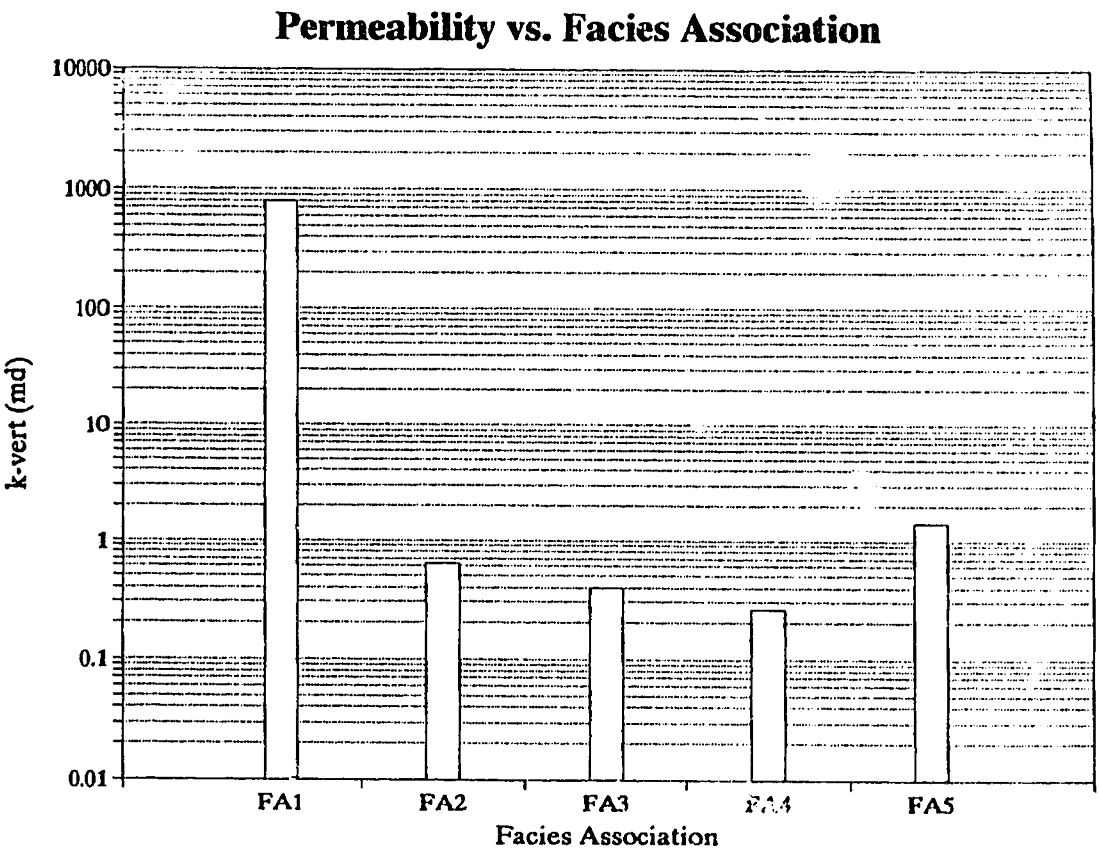


Figure 42. Histogram of average vertical permeability values measured from various facies associations within the Aitken Creek Field. Fluvial channel-fill conglomerates (FA 1) show the highest average vertical permeability, with other various facies associations displaying significantly lower values (< 8 mD) (FA 2: estuarine channel/ tidal channel-fill; FA 3: abandoned estuarine channel/ point bars; FA 4: subtidal estuarine bay-fill; FA 5: transgressive shoreface) N= 23.

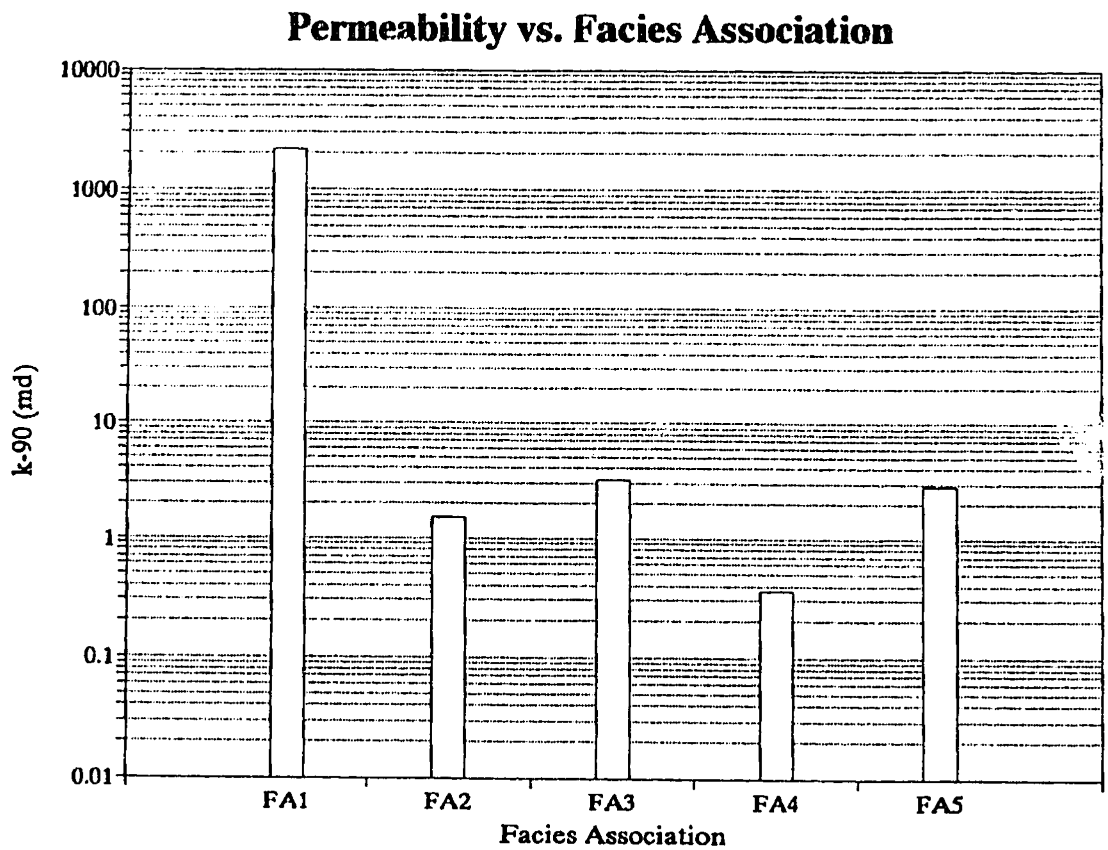


Figure 43. Histogram of average horizontal permeability values measured from various facies associations within the Aitken Creek Field. Fluvial chann l-fil' conglomerates (FA 1) show the highest average horizontal pe with various other facies associations displaying significantly lo 6 mD) (FA 2: estuarine channel/ tidal channel-fill; FA 3: aban ne channel/ point bars; FA 4: subtidal estuarine bay-fill; FA 5: ve shoreface) N= 23.

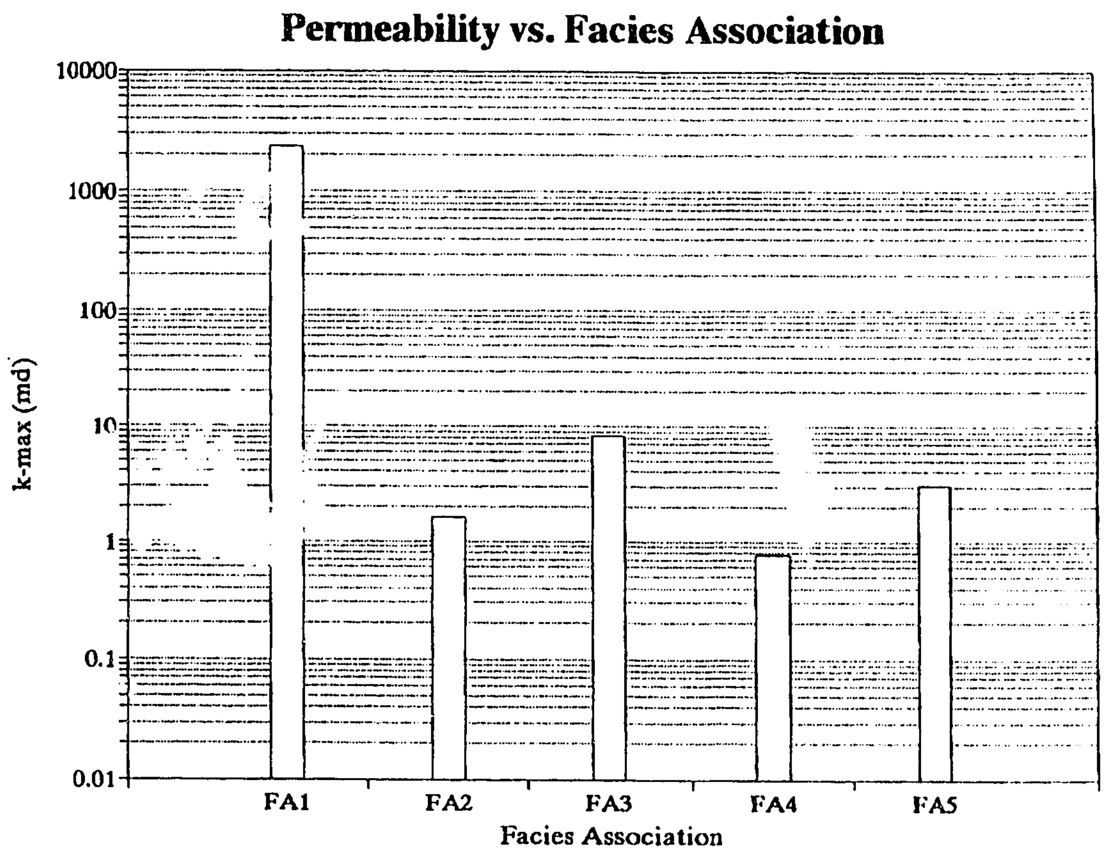


Figure 44. Histogram of average maximum permeability values measured from various facies associations within the Aitken Creek Field. Fluvial channel-fill conglomerates (FA 1) show the highest average maximum permeability, with other various facies associations displaying significantly lower values (< 8 mD) (FA 2: estuarine channel/ tidal channel-fill; FA 3: abandoned estuarine channel/ point bars; FA 4: subtidal estuarine bay-fill; FA 5: transgressive shoreface) N= 23.

among all facies associations. The average porosity values of the fluvial channel-fill facies association are 4 to 8 percent higher than other facies associations within the Bluesky Formation, and the distributary channel-fill facies association of the Gething Formation. Estuarine channel, abandoned estuarine channel/ point bar, bay-fill, and transgressive shoreface facies associations have relatively lower porosity values, with lowest average porosity observed in estuarine point bar/ abandoned channel fills (Table 8).

Variations in maximum permeability (K-max, K-vert, K-90) are quite significant among the various Bluesky facies associations. Maximum permeabilities are highest in fluvial channel fills, and significantly lower in estuarine channel, pointbar-abandoned channel, bay -fills and transgressive shoreface deposits. Some reservoir quality is observed in conglomeratic transgressive shoreface deposits. However, this facies association is thinner, does not extend over a broad area, and is prone to rapid lateral changes from shoreface chert-sublitharenite conglomerate to offshore litharenite sandstone and mudstone. Estuarine channel and point bar facies associations have fair porosities, but extremely low vertical permeability due to tidal bundles and interbedded mudstones and siltstones. Horizontal permeablilities are slightly better, due to the lateral continuity of sandstone units separated by mudstone interbeds.

Based on porosity and permeability cross-plots (Fig. 45, 46), fluvial channel fills can easily be distinguished from Gething distributary channels which have significantly reduced reservoir quality (Fig. 48). Petrologic and scanning electron microscope analysis shows that maximum

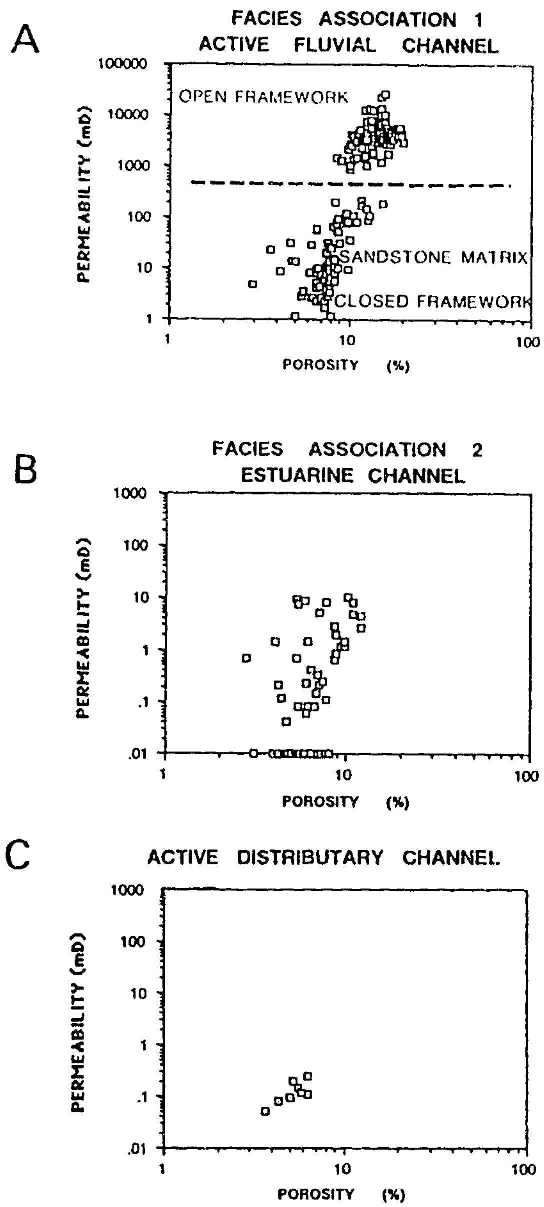


Figure 45. Porosity-Permeability cross-plots of fluvial (A), estuarine (B) and distributary channel (C) facies associations, Aitken Creek Field. Fluvial channel conglomerates (A) show a bimodal distribution of data points attributed to bedform, grain size, and diagenetic controls on reservoir quality. Poor reservoir quality facies characterized distributary channels (C)

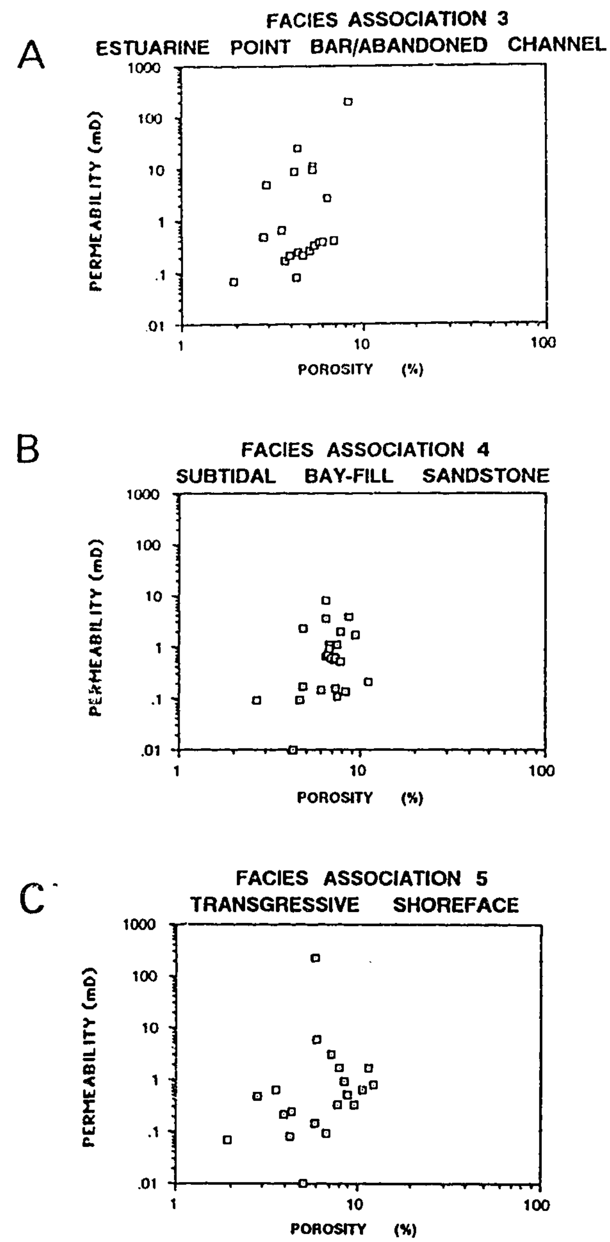
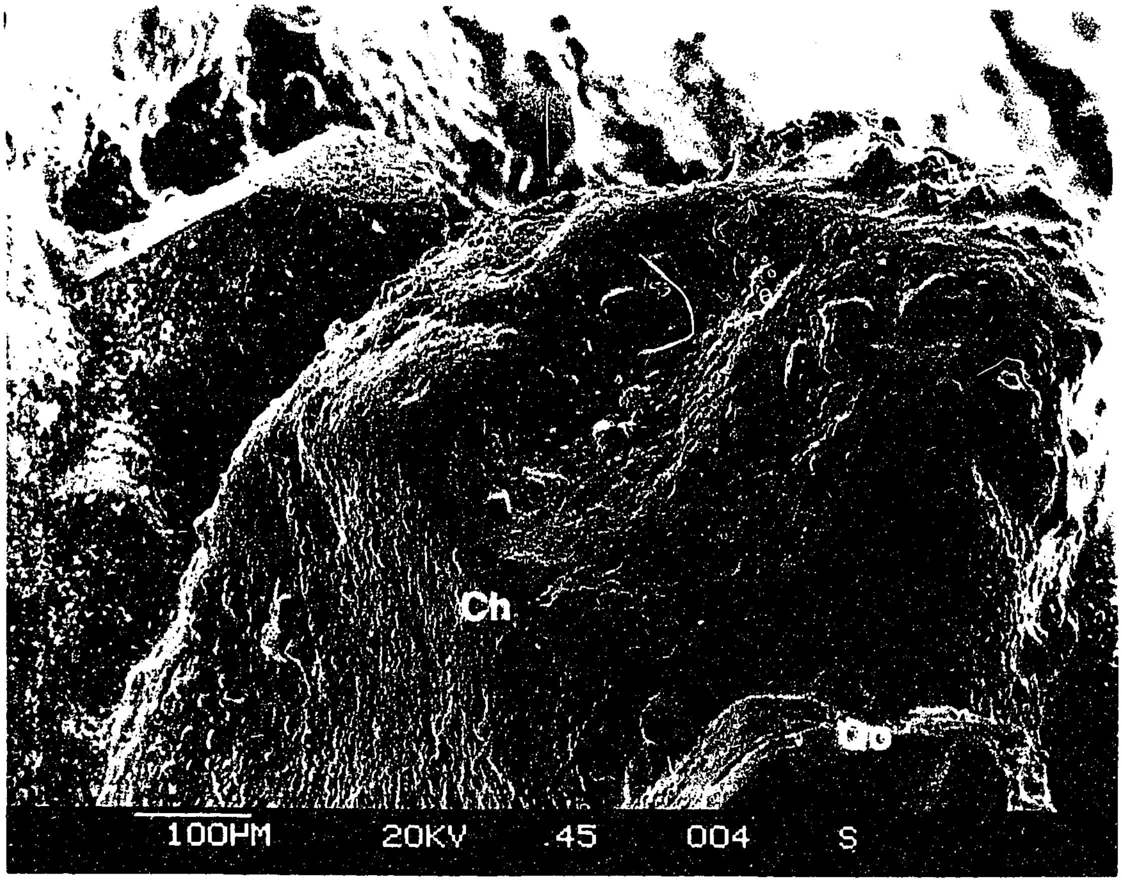


Figure 46. Porosity-Permeability cross-plots of estuarine valley-fill facies associations and transgressive shoreface facies association. Compared to figure 45A, these facies associations show significant reductions in porosity and permeability, and thus, have poor reservoir potential in the Aitken Creek Field.

permeability and primary porosity have been significantly reduced by extensive quartz overgrowths, megaquartz, chalcedonic quartz cements, siderite and minor authigenic pyrite cementation in the estuarine and transgressive shoreface facies and by the presence of illite and smectite in the transgressive shoreface facies (Plate 16, 17). Primary porostiy has additionally been reduced by at least 2 compaction phases within the valley fill. Estuarine and transgressive shoreface sublitharenites rarely exceed 7% porosity. Assuming a depositional porosity of 40% (Davies et al., 1993), then these sublitharenites have lost more than 80% of thier original porosity due to compaction and burial diagenesis. Fluvial channel chert sublitharenite- to litharenite conglomerates show the effects of compaction in the form of pressure solution, styolitic and concavo-convex contacts (Plate 16). An early quartz cementation phase within the chert sublitharenite to litharenite conglomerates may have made this reservoir facies able to withstand better the effects of compaction and dissolution during later burial, thus preserving primary porosity.

The fluvial channel-fill facies association has the highest permeabilites and porosities, and thus is the best reservoir facies (Fig. 47). Fluvial channel-fill facies association porosity and permeability data shows a bimodal distribution of permeability values. The high permeability population is attributed to open framework, clast-supported conglomerates deposited in upper flow regime conditions as massive appearing to plane laminated beds and lower flow regime trough cross-bedded units with a clast size that ranges between 4 to 32 mm (avg. 6 mm) (Fig. 45a). The lower permeability population (Fig. 45a) shows a decrease in reservoir quality

Plate 16. Scanning electron microscope photographs of reservoir quality fluvial conglomerates. A). Chert pebble (Ch) with pressure solution scar and quartz overgrowth (Qo) cements; B) Quartz grains (Qtz) showing solution etching and preservation of porosity (Po).


Ch
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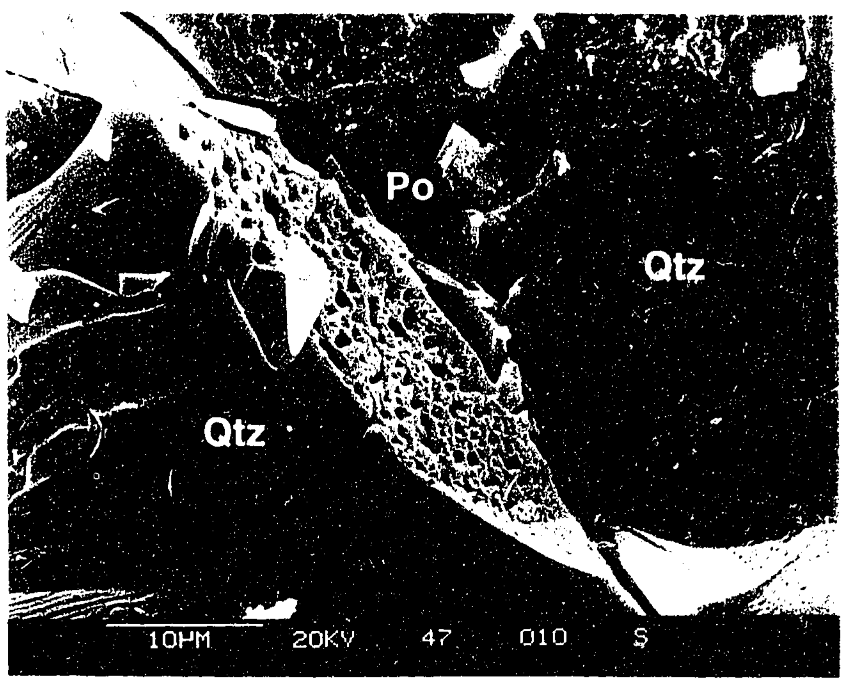
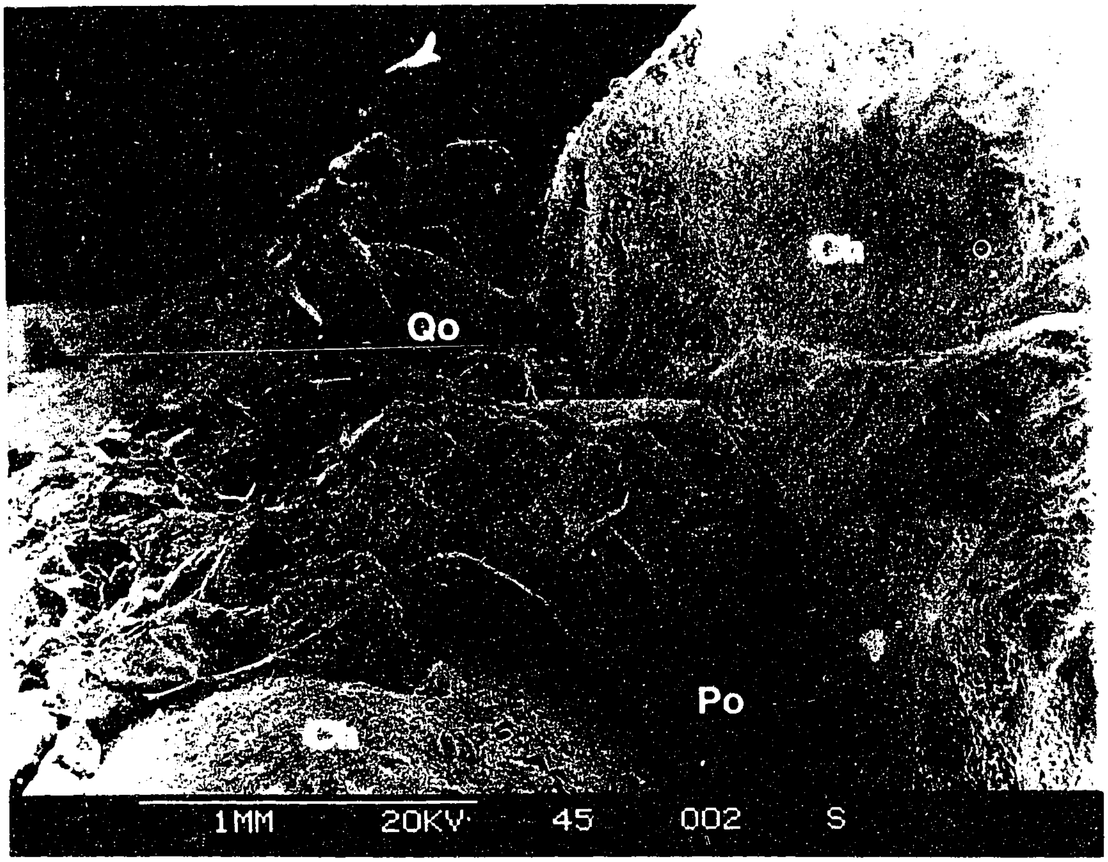
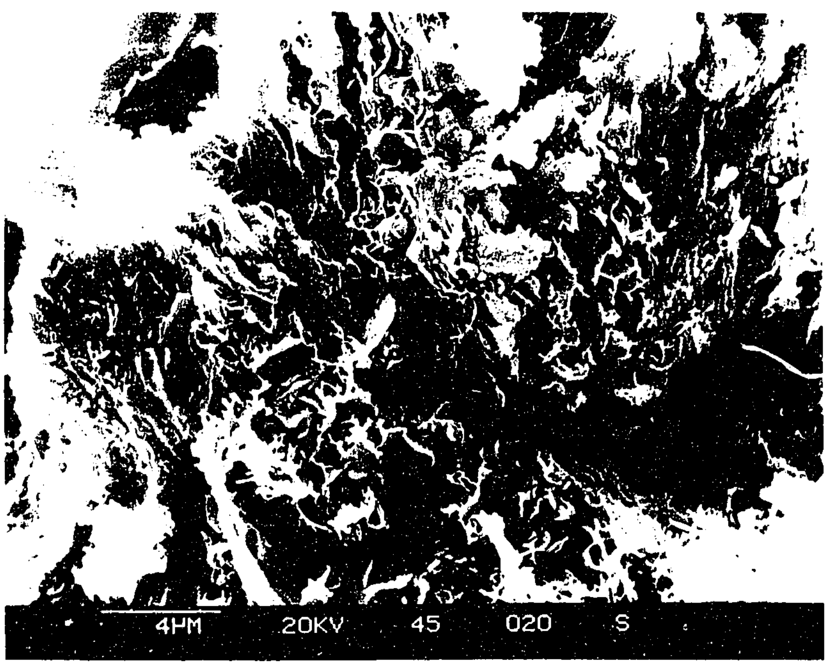

Po
Qtz
Qtz
10µM
20KV
47
010
S

Plate 17. Scanning electron microscope photographs of diagenetic cements and detrital clays within the main reservoir, Aitken Creek Field. A). Framework grains of Chert (Ch) cemented by quartz overgrowths (Qo) which do not completely reduce the reservoir quality, as illustrated by the preservation of porosity (Po). B). Detrital illite clay is commonly associated with channel lags or lateral accretion surfaces within reservoir conglomerates.


Qo
Po
1MM 20KV 45 002 S


4µM 20KV 45 020 S

attributable to a decrease in grain size and sorting, and an increase in sandstone matrix, with smaller pore spaces that become more readily occluded by quartz overgrowths (Plate 17A), megaquartz, chalcedonic quartz and siderite cements (Fig. 48). Detrital illite rarely occurs within the fluvial active channel facies but is commonly associated with channel lags and lateral accretion surfaces (Plate 17B). The absence of feldspars in fluvial reservoir facies suggests that reservoir quality will not be affected by authigenesis (i.e. sericite or illite).

Transgressive shoreface reservoir facies character can easily be distinguished from estuarine valley fill reservoir facies which displays a wide dispersion of data points, generally lower permeabilities and wide range in porosity (Fig.45 & 46). Therefore, the data presented in figures 41, 42, 43, 44, 45, 46, 47, and 48 suggests that permeability in the fluvial channel-fill facies association is directly correlateable to conglomerate framework, texture and lithology (i.e. clast- vs. matrix-supported conglomerate), and indirectly to the style of cross-bedding (T.F. Moslow, pers. comm., 1994). Higher permeable conglomerate (clast-supported, open framework) is deposited under higher current velocities (possibly upper flow regime conditions) and most probably in axial or deeper parts of the incised fluvial channel. Thus, these more incised fluvial sediments are: a) more prone to preservation during transgression; but b) isolated in terms of reservoir continuity from other facies and themselves. Diagenesis has influenced these chert sublitharenite to litharenite conglomerates, but has done so in the framework established by the hydrodynamics of sedimentation in the original depositional environment (Davies et al, 1993).

9.3.0. TRAP STYLE:

The trapping mechanism of hydrocarboons within reservoir quality conglomerates and sandstones of the Aitken Creek Field appears to be structural and stratigraphic (Fig. 28). Fluvial incised valleys are oriented northeast-southwest, within a broad structural sag (Fig. 38), resulting from basement-involved tectonism associated with the Hay River Fault zone, Gething Formation paleotopography, or a combination of both (Fig. 49). Fluvial channel reservoir facies occur in the deepest position within the incised valley, in structural or topographic lows. The oil and natural gas pools have average gross pay thicknesses of 4.5 m and 15 m, respectively. An oil-leg is present on either side of major reservoir cross-cutting normal faults (Fig. 28). The oil leg has become structurally offset and compartmentalized as a result of basement fault reactivation responding to compressional tectonic stresses within the rising Cordillera to the west. Hydrocarbon emplacement in the reservoir appears to pre-date later Albian faulting events, with an inclined gas/ oil contact dipping at 0.25^{o}- 0.50^{o} to the west-northwest in the reservoir (Fig. 28). Faulting is considered to pre- and post-date valley incision and subsequent deposition of reservoir facies, and post-date the emplacement of hydrocarbons within the Aitken Creek Field. Cross-bedded chert sublitharenite to litharenite reservoir conglomerates are sealed laterally by either: a) interdistributary bay-fill mudstones, siltstones sandstones and coals of the Gething Formation and up-dip by estuarine point bar, abandoned channel mud plugs and tightly cemented subtidal bay-fill muddy sandstones and transgressive shoreface sandstones, or b) along fault displacements where reservoir facies are juxtaposed against tightly cemented subtidal bay-fill muddy sandstones and transgressive shoreface sandstones.

9.4.0. Reservoir Geometry and Heterogeneity

9.4.1. Permeability Barriers

Possible permeability barriers in the Bluesky Formation include: (1) extensively cemented point bar facies association that cap a relatively thick sequence of fluvial channel chert sublitharenite to litharenite conglomerates; (2) lateral facies changes within the valley fill sequence; (3) polymodal and polymictic matrix-supported chert litharenite conglomerate at the base of fining-upward sub-cycles in fluvial channel conglomerate (channel lag facies); and (4) normal faults cross-cutting the reservoir. The relative importance of estuarine point bars as potential seals or permeability barriers is significant in the trapping of hydrocarbons. Average permeabilites for estuarine point bars are extremely low, and these facies overlie locally porous and permeably fluvial chert sublitharenite to litharenite conglomerates. Therefore, these tightly cemented estuarine channel lags, and fine grained estuarine channel and point bar sandstones serve as vertical permeability barriers and, possibly stratigraphic seals. Lateral facies changes from active channel to point bar to abandoned channel plug facies within the upper estuary display a substantial decrease in vertical, horizontal and maximum permeabilities. Fluvial channel fills do not display rapid lateral facies changes and illustrate substantially better permeabilities than upper estuary channels. Channel lag facies (i.e. lateral accretion surfaces) within fluvial chert sublitharenite to litharenite conglomerates display permeability reduction of up to two orders of magnitude when compared to fluvial active channel facies (Fig. 45).

The significance of lateral accretion surfaces must be considering in secondary enhanced hydrocarbon recovery. Lateral accretion surfaces will potentially reduce the rate of hydrocarbon recovery from the main fluvial conglomerate reservoir, in that the migration of hydrocarbons across these surfaces will be relatively slower than through active channel conglomerate (Facies 4A). Normal faults may improve the potential drainage capabilities of a well through fracturing, and thus, improve the communication of reservoir facies within the field.

9.4.2. Reservoir Production

The highest natural gas and oil production rates are obtained from fluvial channel-fill, clast-supported, open-framework conglomerate positioned in structural lows where sedimentation was confined by the walls of the incised valley (IP: 54 to 64 m^3 OPD; 220 000 to 250 000 m^3/d natural gas production; AOF: 125 000 to 150 000 m^3/d). Permeability in the Aitken Creek Field channel tends to decrease to the west and south and is directly correlateable to conglomerate framework, texture and lithology, and indirectly to the style of bedding and cross-bedding. Additional controls on primary porosity and permeability reduction are abundant cementation, or decrease in reservoir facies thickness.

10.0.0. PREDICTIVE MODEL AND EXPLORATION STRATEGIES

The sequence stratigraphic model outlined above has significance for exploration and development of petroleum reservoirs in the Bluesky Formation and other Cretaceous age reservoirs in northeastern British Columbia. The development of a depositional model for Bluesky Formation reservoir facies in the Aitken Creek Field, establishes the first phase in the exploration of valley-fill reservoirs (Fig. 36). The second phase involves exploration for potential reservoirs within the valley and adjacent valleys. Two "high potential" acreage blocks have been identified within the study area (Fig. 50) and one additional "high potential" acreage block outside of the study covering the southeast corner of block B/ 094-H-14 to the northwest corner of block J/094-A-13 . These acreage blocks may present undiscovered fluvial incised valley fills based on the depositional model developed at Aitken Creek based on the following rationale.

On a regional scale, Bluesky incised valleys are often localized over topographic lows or along fault trends. Preservation of the Aitken Creek reservoir facies is a function of conglomerate deposition within a structural and/or topographic low in response to the incised valley following the axis of a structural low (Fig. 49). Thus, the recognition of structural features is of paramount importance in the exploration of this play type. Topographic and structural anomalies were recognized from structure mapping of established chronostratigraphic boundaries. Additionally, recognition of valley trends were mapped by isopaching transgressive systems tract parasequences between the basal Buckinghorse marine flooding surface to the Bluesky initial transgressive surface boundary. Thick isopach values reveal potential valley trends and areas of thick Bluesky sediments.

Palinspastic reconstruction of the adjacent western fold and thrust belt west of the present study, may yield clues to the location of thick aggrading fluvial channel-fill sequences associated upstream from mapped incised valley trends. However, valley fill deposits within this setting, as stated by Schumm (1993), are controlled by base-level changes in response to tectonic uplift or climate rather than eustatic sea-level fluctuations. Therefore, understanding the primary controls on base-level fluctuations is of key importance in the search for fluvial channel-fill deposits within incised valleys in foothills locations west of the study area.

The geological mapping present in this study should incorporate additional well log information and seismic reflection data to increase the resolution of valley trends and outlined areas of "high potential". Seismic reflection data will better assess the structural features which influenced Bluesky fluvial drainage patterns within the study. The incorporation of seismic reflection data will better assess the divergence and local widening of the incised valley illustrated in the isopach of Bluesky Parasequence 1 in the area of the Aitken Creek Field (Fig 32). Other areas displaying divergence and local widening of the incised valley and potentially containing lowstand fluvial conglomerate reservoirs may be predicted by incorporating the depositional model for the Bluesky Formation developed in the Aitken Creek Field along the valley trend.

11.0.0. CONCLUSIONS

1. Twelve facies are recognized and described from cored intervals of the lithostratigraphic Bluesky Formation in the Aitken Creek Field. These are grouped into the following five commonly occuring vertical facies associations: 1) fluvial channel-fill; 2) estuarine channel-fill; 3) abandoned estuarine channel-fill/ point bars; 4) subtidal estuarine bay-fills; and 5) transgressive shoreface.

2. Conglomerates and sandstone deposits within the Aitken Creek Field were deposited by fluvial, estuarine and marine processes during the late lowstand and subsequent transgression of the Moosebar/ Wilrich sea. This transgressive-regressive couplet represents a fouth order cycle in the sense of Vail *et al.* (1991). It is likely that the transgressive-regressive couplets of the early Cretaceous were strongly influenced by both eustasy and tectonics.

3. Within the Aitken Creek Field, there are five parasequences, BP 1 through BP 5, bounded by either sequence boundaries marine flooding surfaces or transgressive surfaces of erosion. An unconformity at the base of fluvial conglomerates reflects a break in depositon between the Gething Formation and Bluesky Formation in the study area and is interpreted as a Type-1 sequence boundary.

4. Previous depositional interpretations of the Bluesky Formation suggest the dominance of transgressive deposits (i.e. transgressive lags, sheet sands, shoals, etc). However, within the Aitken Creek Field, the Bluesky Formation is interpreted to consist of a series of stacked parasequences or parasequence sets which show an

overall decrease in fluvial dominance upward and progressive marine influence during transgression of the incised valley.

5. The lowstand systems tract is expressed as a one-channel thick deposit of clast-supported conglomerate and pebbly sandstones in the thalweg of the incised valley. The incised valley, during the early lowstand of sea level, is considered a zone of sediment by-pass. It is not until the late lowstand of sea level that conglomerates and pebbly sandstones are deposited within the incised valley, and trapped during the transgression by the landward migrating bay-line, which become overlain by estuarine sediments. This contact represents the initial transgressive surface. The preservation of fluvial sediments may be a function of a) localized fluvial incision, and/ or b) tectonic controls related to reactivation of basement structures (i.e. Hay River Fault zone).

6. The transgressive systems tract comprises the majority of the valley-fill, consisting of facies that were deposited in four facies associations comprising estuarine channel, abandoned estuarine channel/ point bar, subtidal estuarine bay, and transgressive shoreface facies. Marine flooding surfaces, tidal ravinement surfaces and wave ravinement surfaces sub-divide the transgressive systems tract into five parasequences.

7. Fluvial channel-fill conglomerates display the best reservoir quality, compared to estuarine and transgressive shoreface facies. Primary porosity is strongly influenced by the depositional environment, bedforms, grain-size sorting, and diagenetic cementation. Significant reduction in reservior quality is attributed to compaction and diagenetic quartz overgrowth cementation. The emplacement of hydrocarbons post dates pre-Aptian faulting and valley incision; however, predates major normal faults

which intersect the valley fill and extend upwards into the Buckinghorse Formation (Post early Albian ?). Potential permeability barriers within the reservoir include: (1) estuarine channel lags, (2) lateral accretion surfaces, and (3) sealing normal faults. Interdistributary bay-fills form lateral seals for lowstand fluvial conglomerate reservoirs. Updip seals are in the form of estuarine channel plugs, or fault offsets against transgressive shoreface sandstones and mudstones and open marine mudstones.

8. Because of the inherent complexity of facies transitions within an estuary, hydrocarbon bearing reservoir facies will be more difficult to predict compared to fluvial reservoir facies.

9. The stratigraphic framework and depositional model developed for the Aitken Creek Field suggests that in-place hydrocarbon reserves for the Bluesky Formation in northeastern British Columbia may be greatly under estimated in that they are incorporated within the in-place hydrocarbon reserves of the underlying Gething Formation. Further regional exploration success of this play type will require an improved understanding of the details of lateral correlations and facies changes and basement-involved structural controls influencing incised valleys. Therefore, this study can be applied to development strategies of existing reserviors and in improving upon exploration for reserviors of this play type throughout the Western Canada Sedimentary basin.

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APPENDIX A - CORE DESCRIPTIONS

LEGEND

REFER TO TABLE 7 FOR KEY TO LITHOLOGY, SEDIMENTARY, AND ICHNOLOGY SYMBOLS USED IN CORE DESCRIPTIONS.

GETHING FACIES ASSOCIATIONS

GFA1 - INTERDISTRIBUTARY BAY-FILL
GFA2 - DISTRIBUTARY CHANNEL-FILL

BLUESKY FACIES ASSOCIATIONS

FA1 - FLUVIAL CHANNEL-FILL
FA2 - ESTUARINE CHANNEL FILL
FA3 - ABANDONED ESTUARINE CHANNEL/ POINT BAR
FA4 - SUBTIDAL ESTUARINE BAY-FILL
FA5 - TRANSGRESSIVE SHOREFACE

BUCKINGHORSE FACIES ASSOCIATION

BFA1 - TRANSGRESSIVE OPEN MARINE SHELF

BLUESKY TRANSGRESSIVE SYSTEMS TRACT PARASEQUENCES

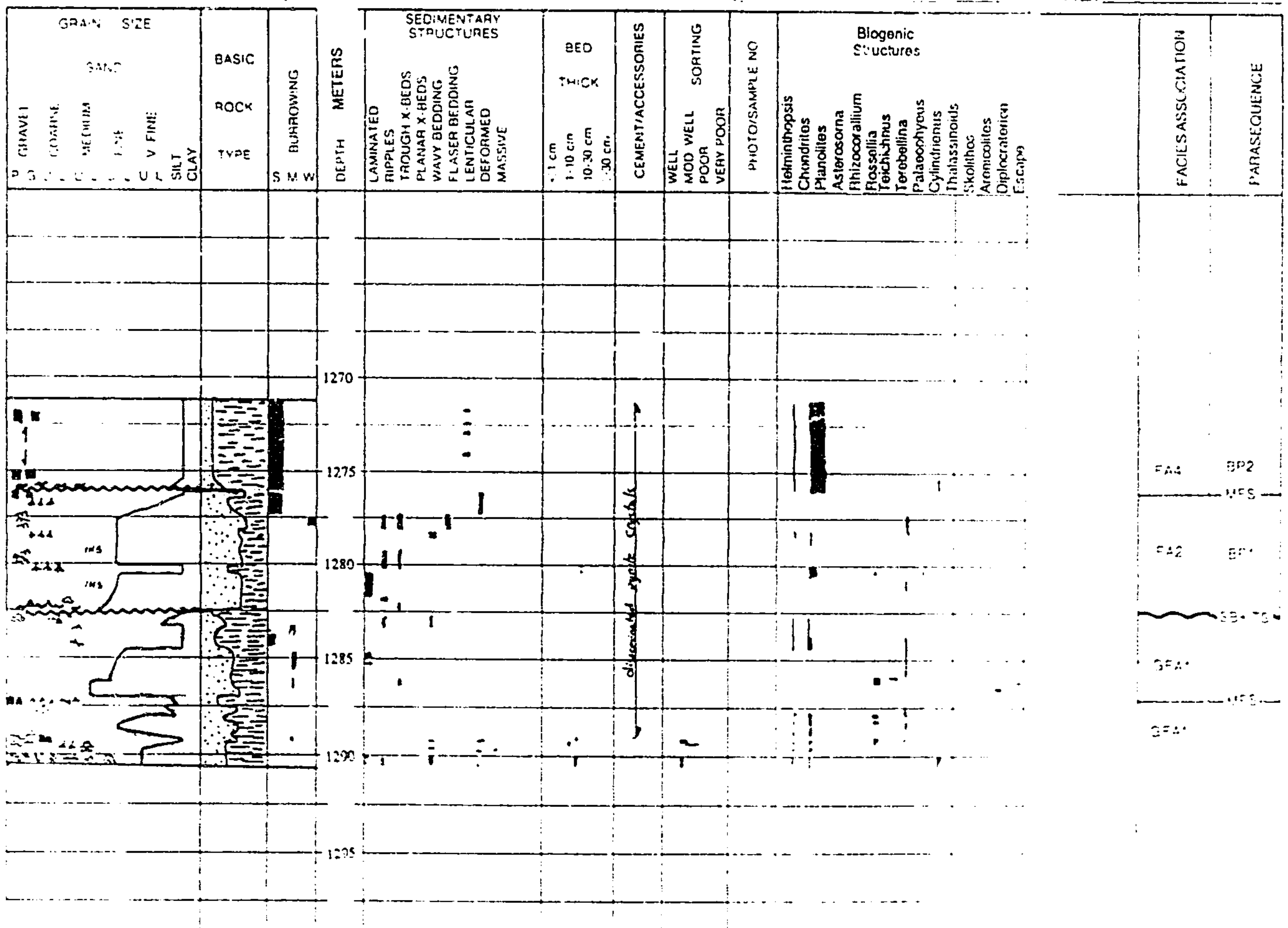
BP1 - MIDDLE- TO UPPER ESTUARY
BP2 - LOWER- TO MIDDLE ESTUARY
BP3 - LOWER- TO MIDDLE ESTUARY
BP4 - LOWER ESTUARY
BP5 - OUTER ESTUARINE EMBAYMENT

AitkenCore Locations

	A	B	C
1	c-028-F/094-A-13	1271.5-1290.5	18.0m
2	d-011-K/094-A-13	1235.4-1248.5	10.7m
3		1248.8-1258.8	10.1m
4	d-019-K/094-A-13	1290.8-1300.3	7.6m
5		1300.3-1306.1	4.3m
6	d-059-K/094-A-13	1271.0-1286.7	15.7m
7	b-064-K/094-A-13	1181.4-1191.5	10.1m
8	b-088-K/094-A-13	1285.0-1296.0	9.7m
9		1296.0-1314.0	16.7m
10	d-003-L/094-A-13	1310.0-1328.0	18m
11	a-005-L/094-A-13	1335.0-1353.3	18.3m
12	d-021-L/094-A-13	1317.5-1335.0	17.5m
13	d-023-L/094-A-13	1313.1-1331.1	4.5m
14	d-024-L/094-A-13	1346.3-1359.1	12.8m
15	d-025-L/094-A-13	1338.4-1353.0	14.6m
16	d-030-L/094-A-13	1294.5-1313.4	18.3m
17	d-033-L/094-A-13	1318.3-1333.5	15.2m
18	d-034-L/094-A-13	1325.9-1348.7	21.9m
19	d-035-L/094-A-13	1347.8-1360.0	12.2m
20	d-041-L/094-A-13	1340.0-1350.0	9.9m
21	b-042-L-094-A-13	1331.7-1348.7	17.1m
22	d-043-L/094-A-13	4379.92-4430.11	14.8 ft
23	d-044-L/094-A-13	1342.9-1354.5	12.3m
24	d-045-L/094-A-13	1354.8-1366.7	11.9m
25		1331.4-1349.7	18.0m
26	d-047-L/094-A-13	1277.4-1291.7	14.8m
27	d-052-L/094-A-13	1300.9-1309.7	6.1m
28	a-053-L/094-A-13	1341.4-1348.4	18.3m
29	b-054-L/094-A-13	1340.0-1348.8	8m
30		1348.8-1351.2	2.4m
31	d-057-L/094-A-13	1287.8-1299.4	7m
32		1299.4-1303.0	2.4m
33		1303.0-1311.6	8.2m
34		1311.6-1313.7	2.1m
35		1313.7-1318.6	4.9m
36	d-059-L/094-A-13	1286.3-1292.4	6.1m
37		1292.7-1310.9	18.3m
38	b-070-L/094-A-13	1341.6-1346.8	4.8m
39	b-003-I/094-B-16	1289.8-1291.3	1.53m
40	b-071-I/094-B-16	1356-1370	14m
41	b-041-A/094-G-01	1271-1284	13m
42	b-043-A/094-G-01	1000-1004	3.8m
43	c-022-C/094-H-04	1260-1277	17m
44	c-099-C/094-H-04	1279-1287.5	7m
45	d-011-D/094-H-04	1306.5-1324.7	18.3m

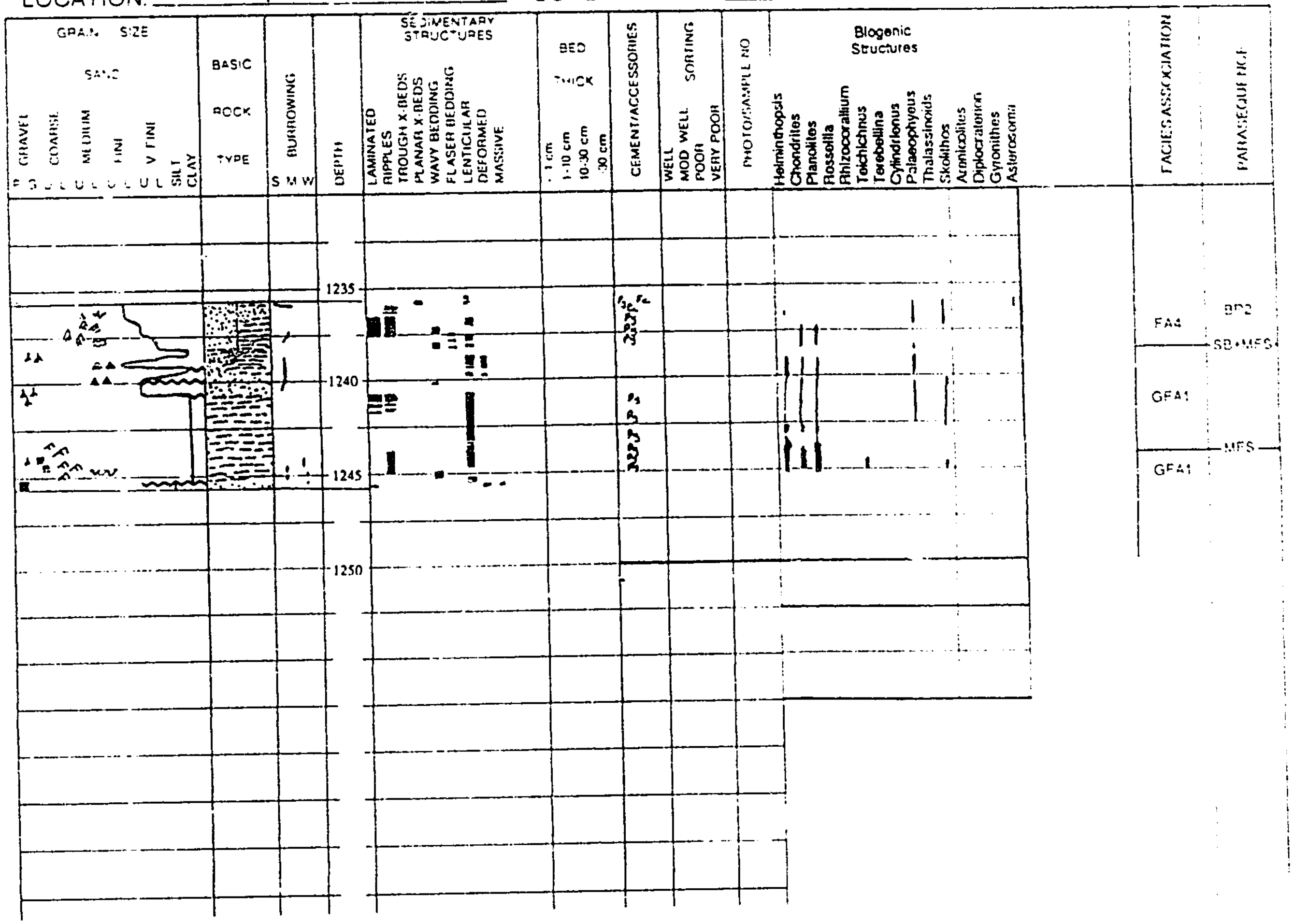
WELL NAME: Can Hunter Pinto FORMATION: Gething DATE: Feb. 1, 1994

LOCATION: c-28-F/94-A-13 CORE INTERVAL: 1272.5 - 1290.5m rec 16.1m KB:



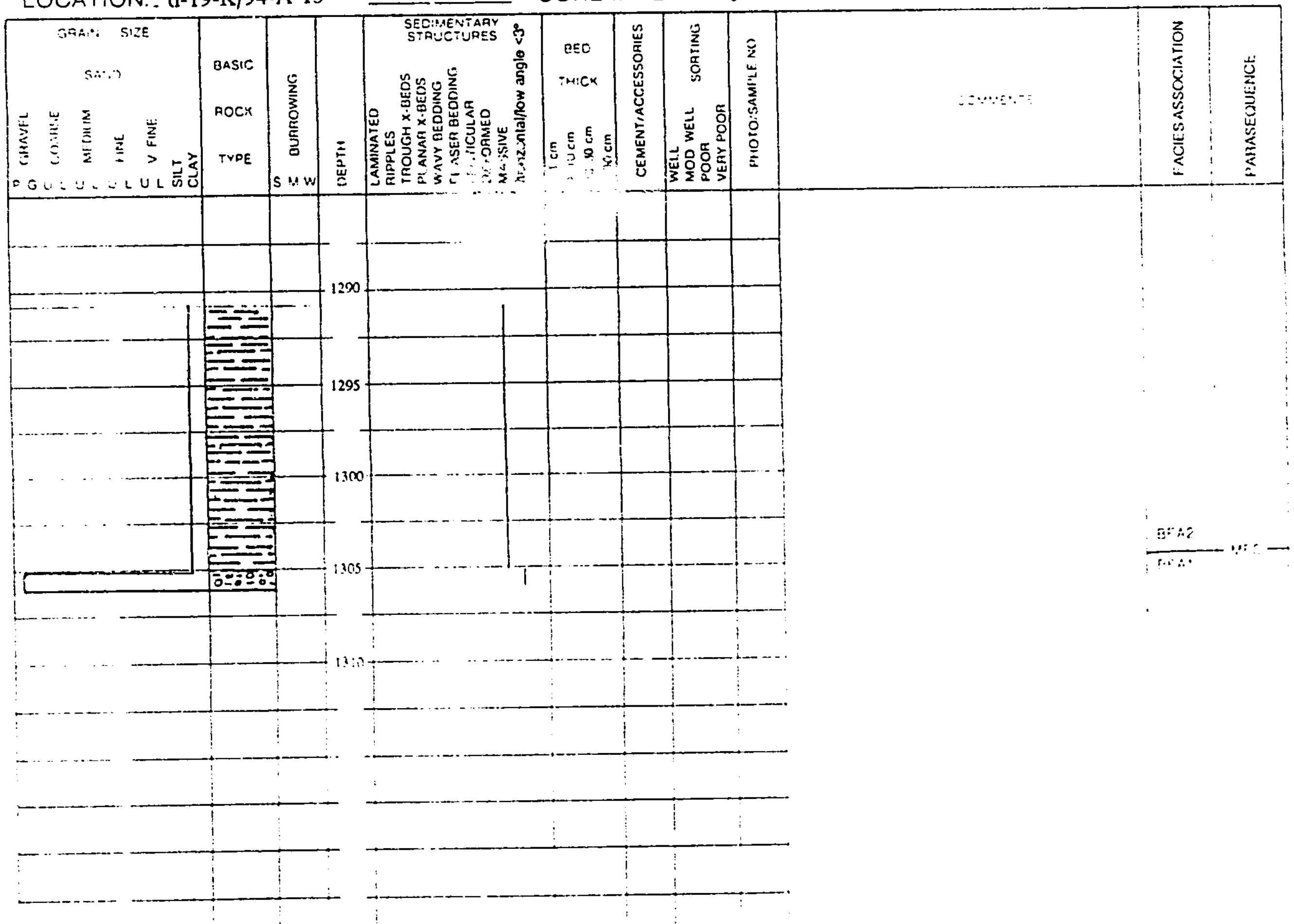
WELL NAME: Aitken Creek FORMATION: Bluesky/Gething DATE: Feb. 22, 1993

LOCATION: d-11-K/94-A-13 CORE INTERVAL: 1235.7 - 1245.7m KB



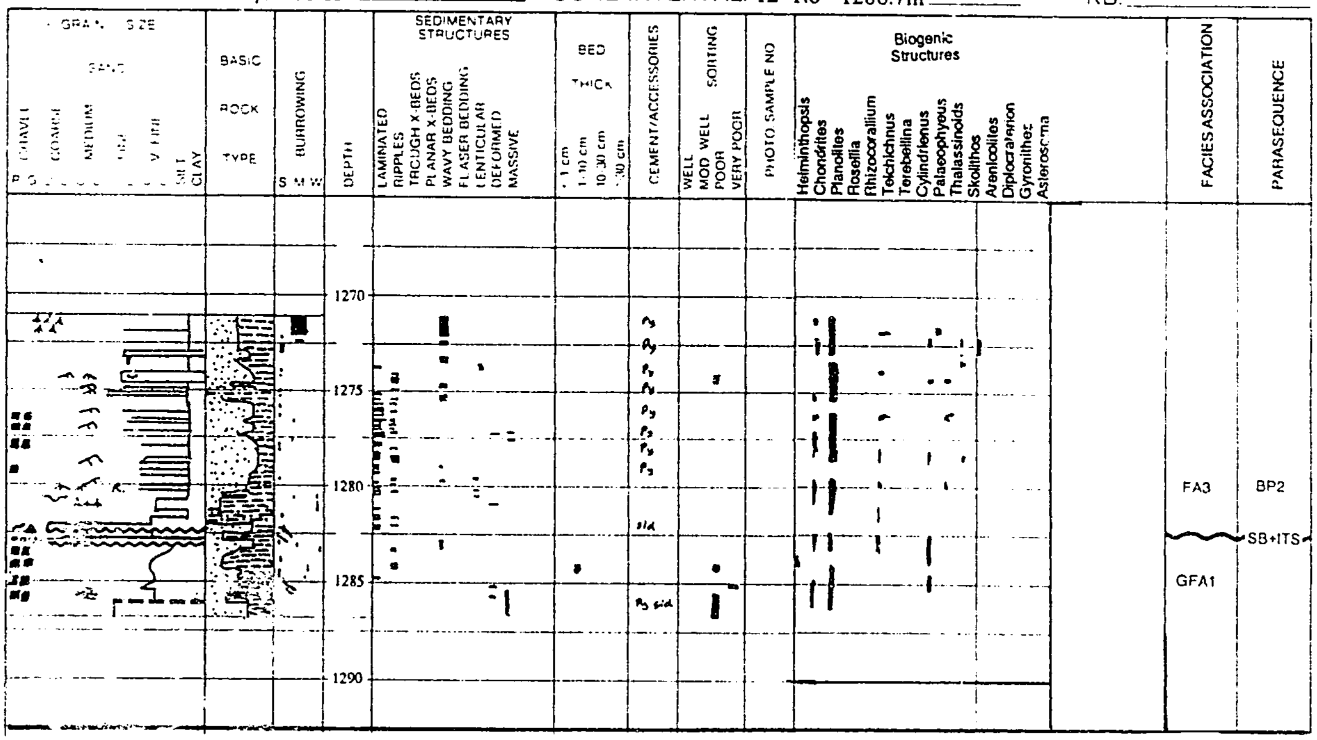
WELL NAME: Union E Aitken FORMATION Bluesky/Wilrich DATE: Feb. 4. 1994

LOCATION: d-19-K/94-A-13 CORE INTERVAL: 1290.8 -1306.1m KB: 931.8m



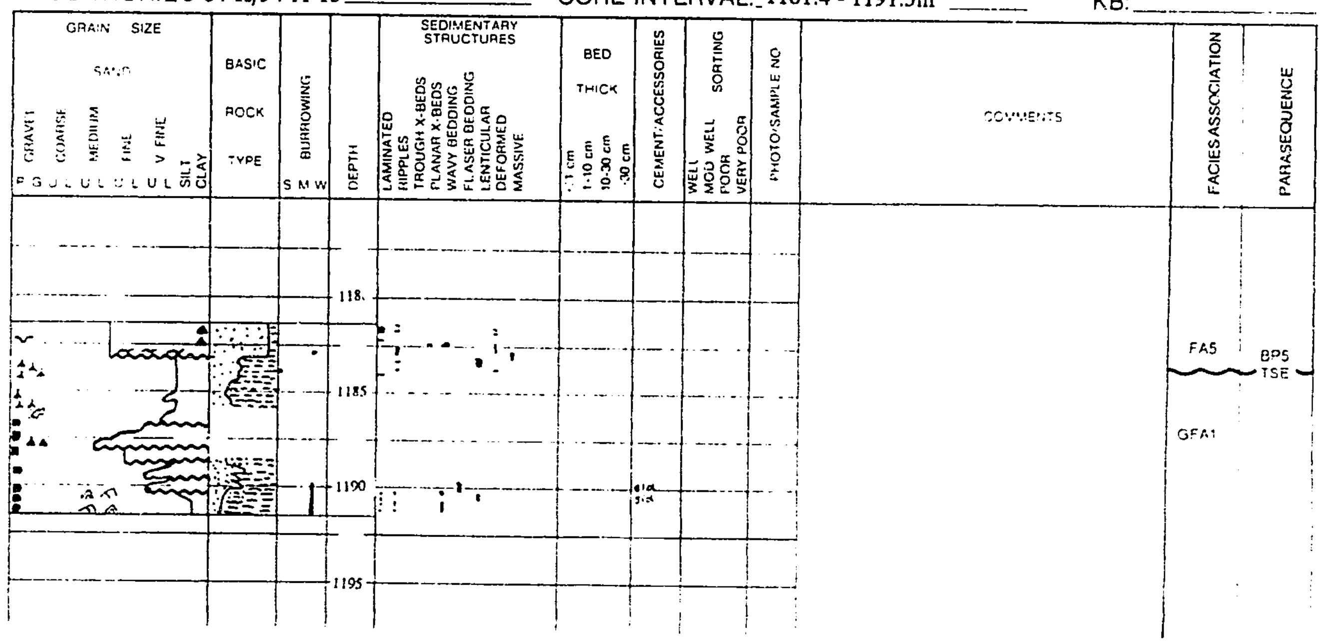
WELL NAME: Encore *et al.* Aitken FORMATION: Gething DATE: Feb. 1994

LOCATION: d-59-K/94-A-13 CORE INTERVAL: 1271.0 - 1286.7m KB:



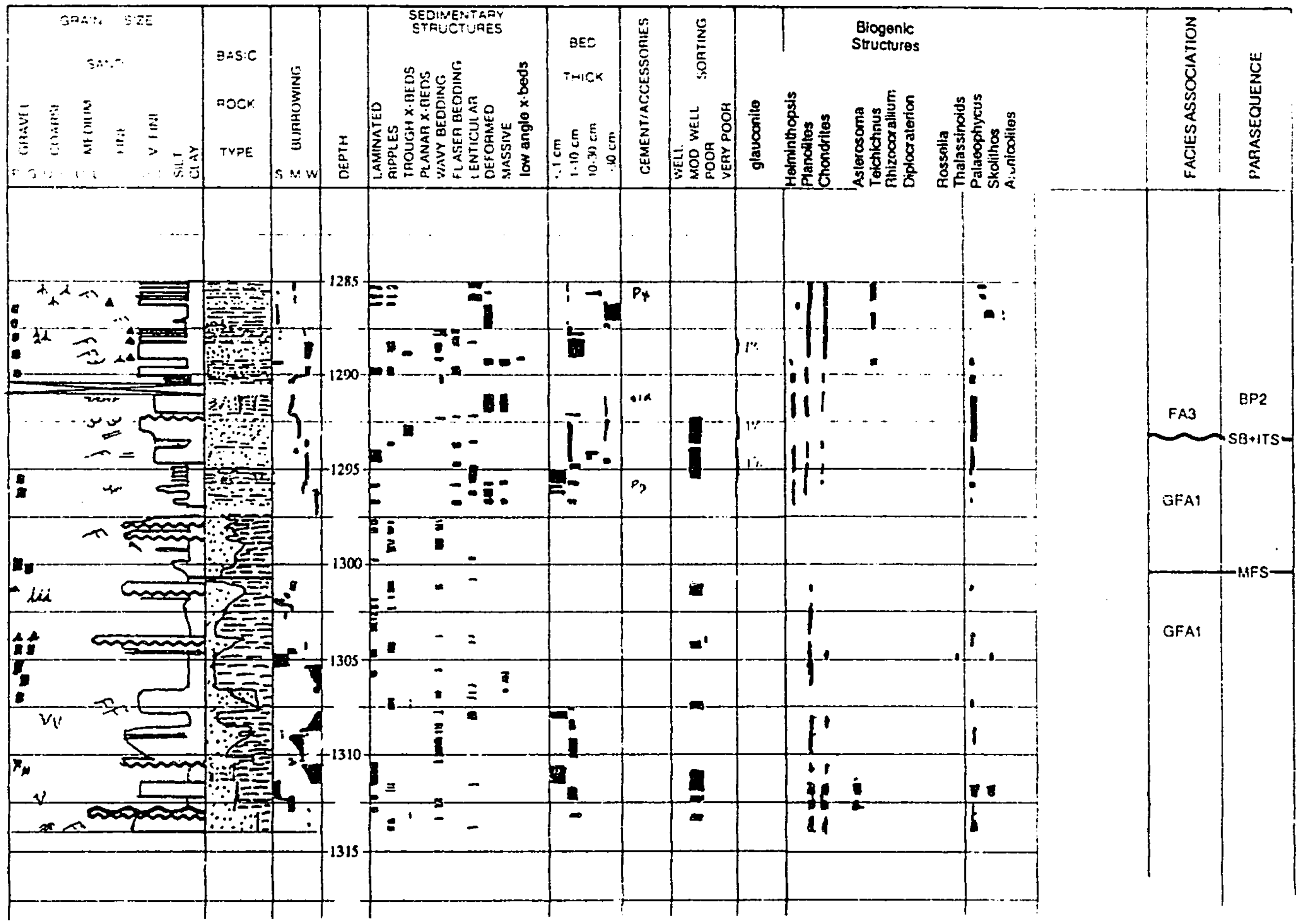
WELL NAME: Union Aspen ____________ FORMATION: Gething ________ DATE: ____________

LOCATION: b-64-K/94-A-13 ____________ CORE INTERVAL: 1181.4 - 1191.5m ______ KB: ____________



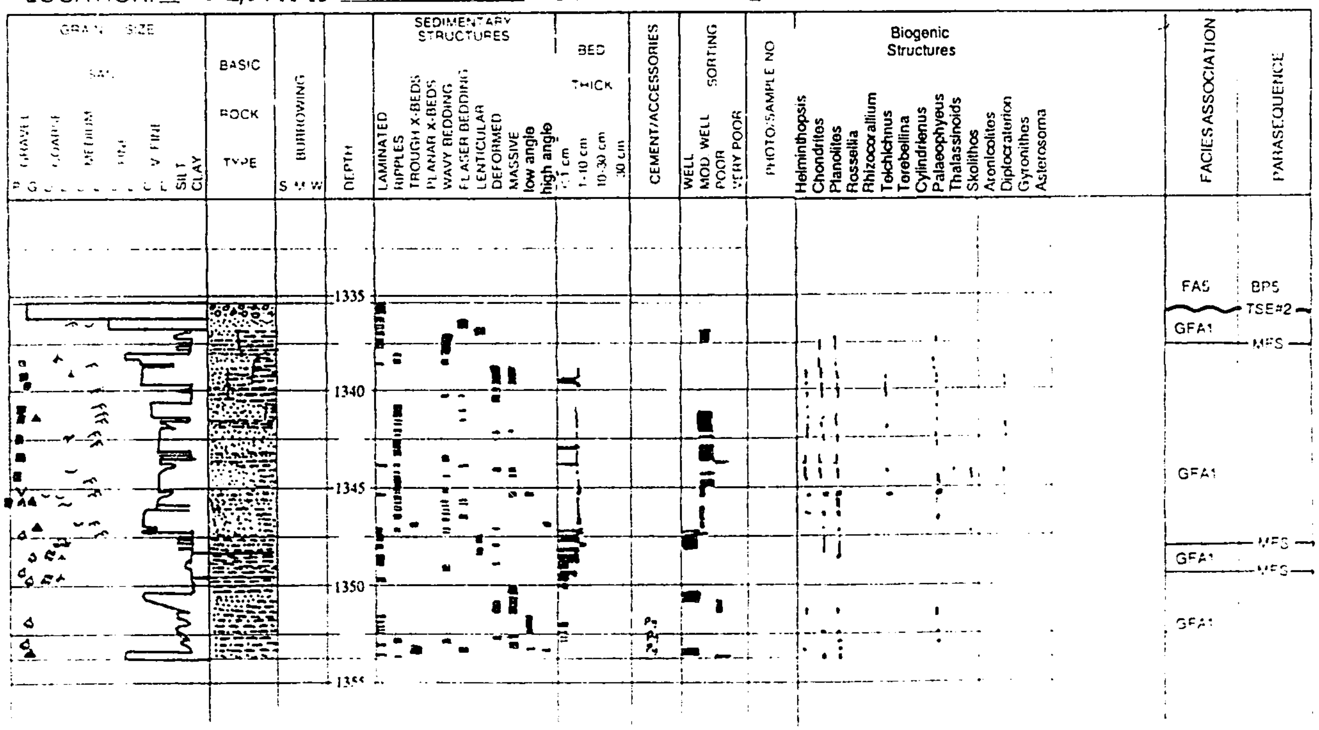
WELL NAME: Aitken Creek/Dome *et al.* West NIG FORMATION: Gething DATE: Feb. 23, 1993

LOCATION: b-88-K/94-A-13 CORE INTERVAL: 1285.0 - 1314.0m KB:



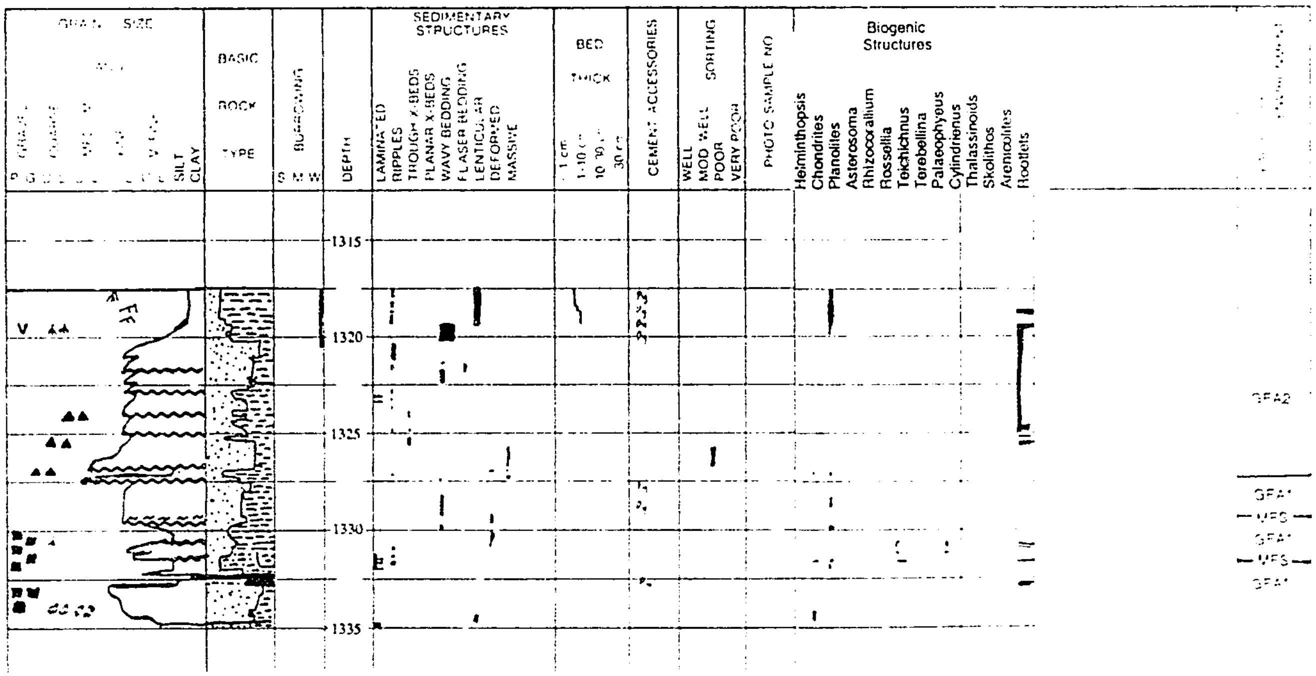
WELL NAME: Union Aitken FORMATION: Bluesky/Gething DATE: Feb. 24, 1993

LOCATION: a-5-L/94-A-13 CORE INTERVAL: 1335.4 - 1353.7m KB:



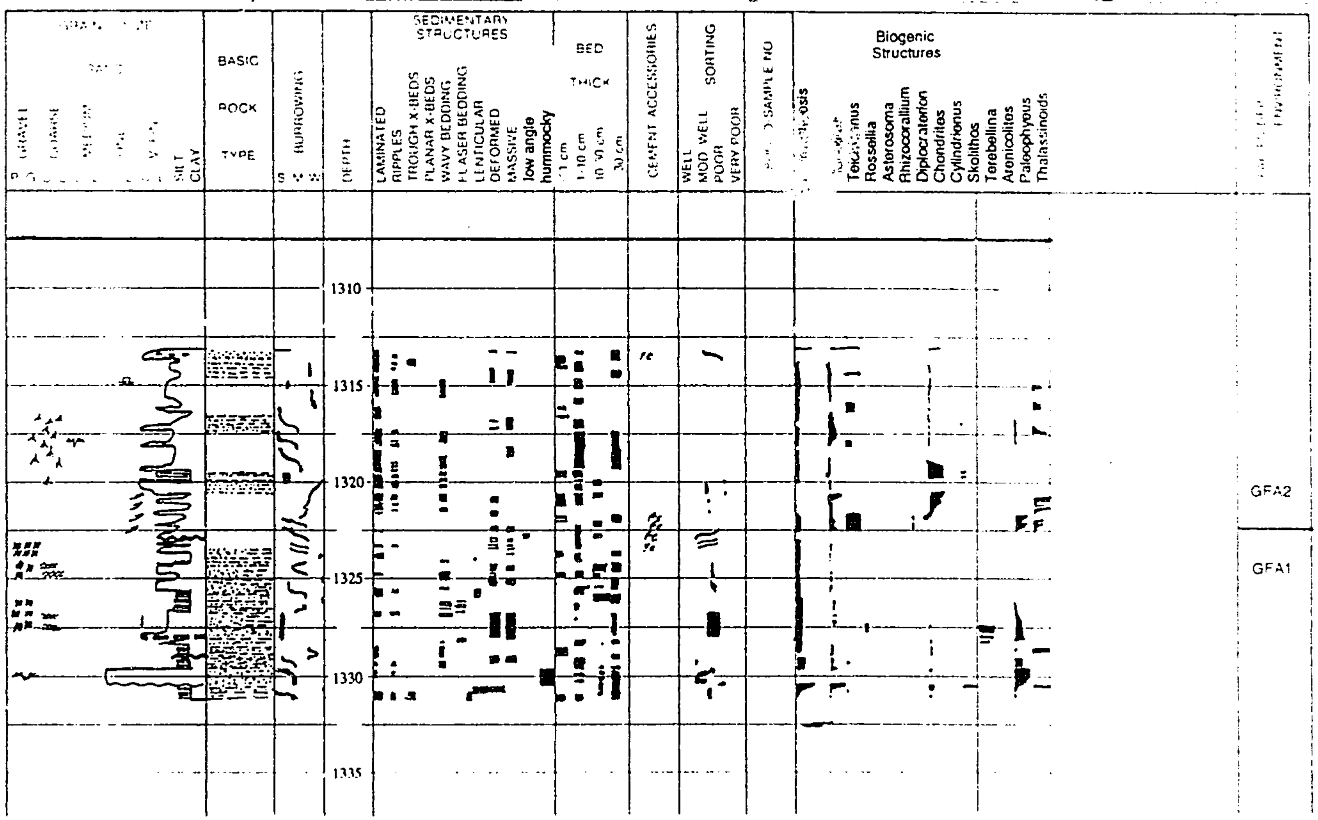
WELL NAME: Union Aitken FORMATION: Gething DATE:

LOCATION: d-21-L/94-A-13 CORE INTERVAL: 1317.5 - 1335.0m KB:



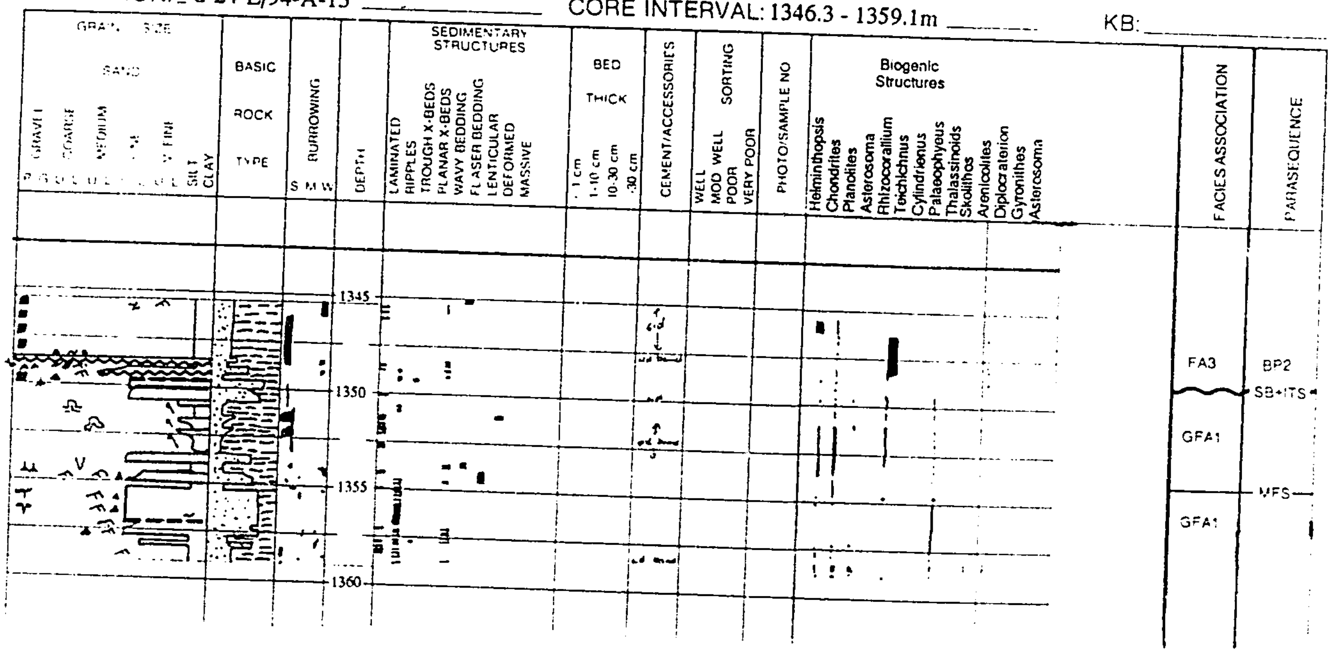
WELL NAME: Union Aitken FORMATION: Gething DATE: Oct. 1992

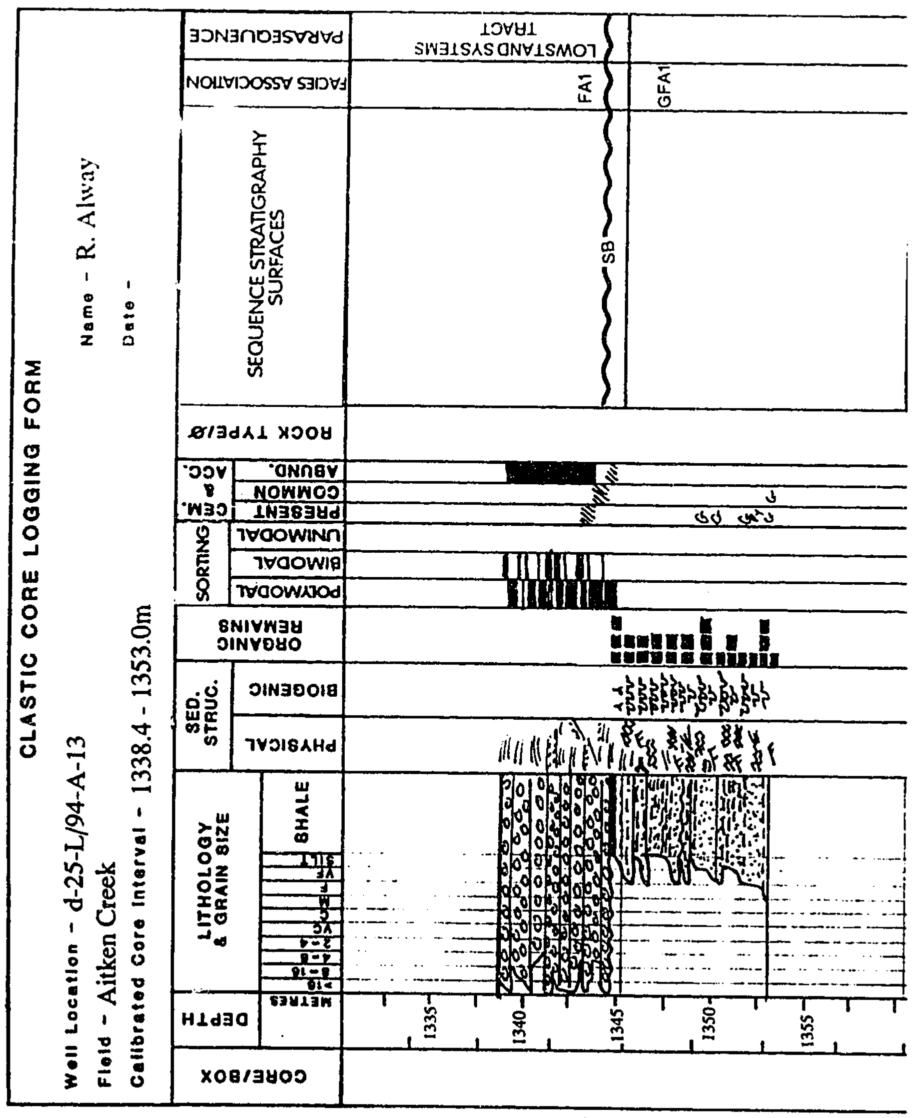
LOCATION: d-23-L/94-A-13 CORE INTERVAL: 1313.1 - 1331.1m KB



WELL NAME: Union Aitken FORMATION: Gething DATE: Feb. 1994

LOCATION: d-24-L/94-A-13 CORE INTERVAL: 1346.3 - 1359.1m KB:




CLASTIC CORE LOGGING FORM
Well Location - d-25-L/94-A-13
Field - Aitken Creek
Calibrated Core Interval - 1338.4 - 1353.0m
Name - R. Alway
Date -
CORE/BOX
DEPTH
METRES
LITHOLOGY & GRAIN SIZE
SHALE
SILT
VF
F
M
C
VC
2-4
4-8
8-16
>16
SED. STRUC.
PHYSICAL
BIOGENIC
ORGANIC REMAINS
SORTING
POLYMODAL
BIMODAL
UNIMODAL
CEM. & ACC.
PRESENT
COMMON
ABUND.
ROCK TYPE/Ø
SEQUENCE STRATIGRAPHY SURFACES
SB
FACIES ASSOCIATION
FA1
GFA1
PARASEQUENCE
LOWSTAND SYSTEMS TRACT
1335
1340
1345
1350
1355

CLASTIC CORE LOGGING FORM

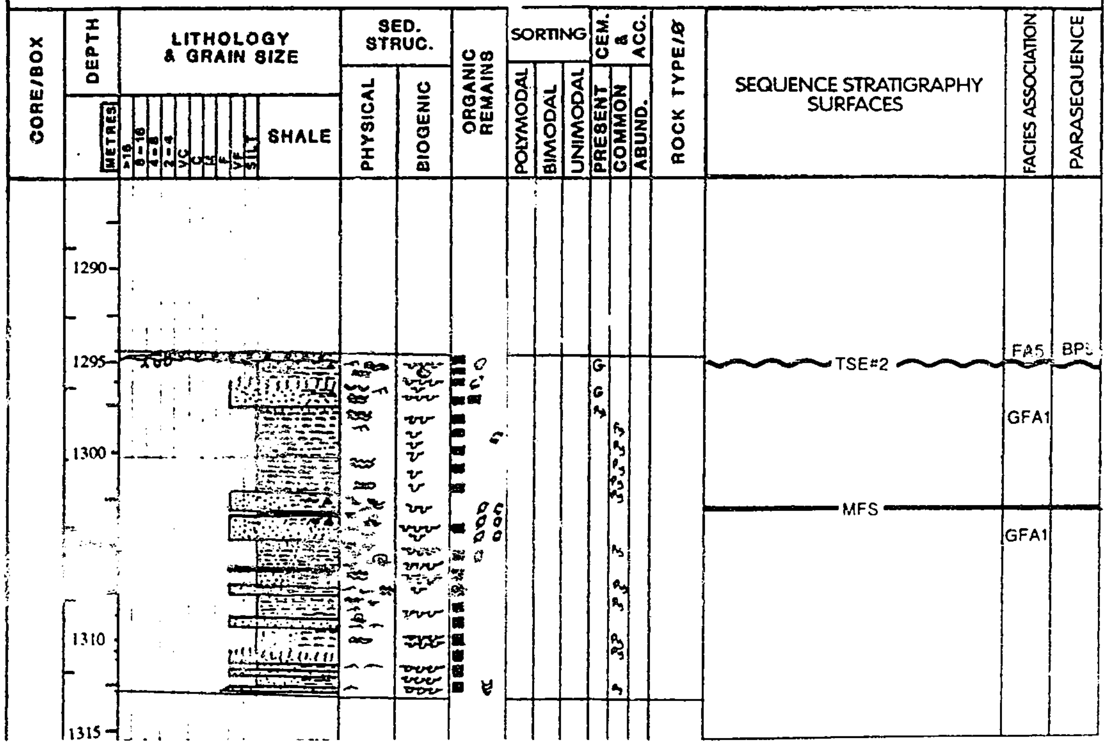
Well Location - d-30-L/94-A-13

Field - Aitken Creek

Calibrated Core Interval - 1294.5 - 1312.8 m

Name - R. Alway

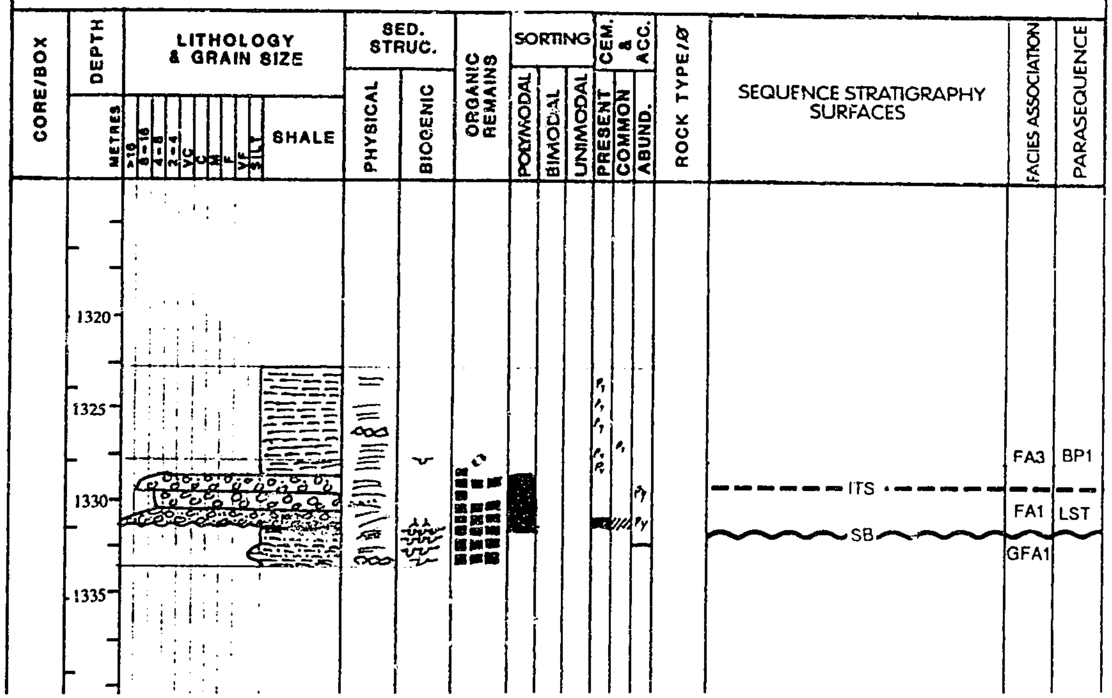
Date - Feb. 25, 1993



CLASTIC CORE LOGGING FORM

Well Location - d-33-L/94-A-13
Field - Aitken Creek
Calibrated Core Interval - 1322.8 - 1333.5m

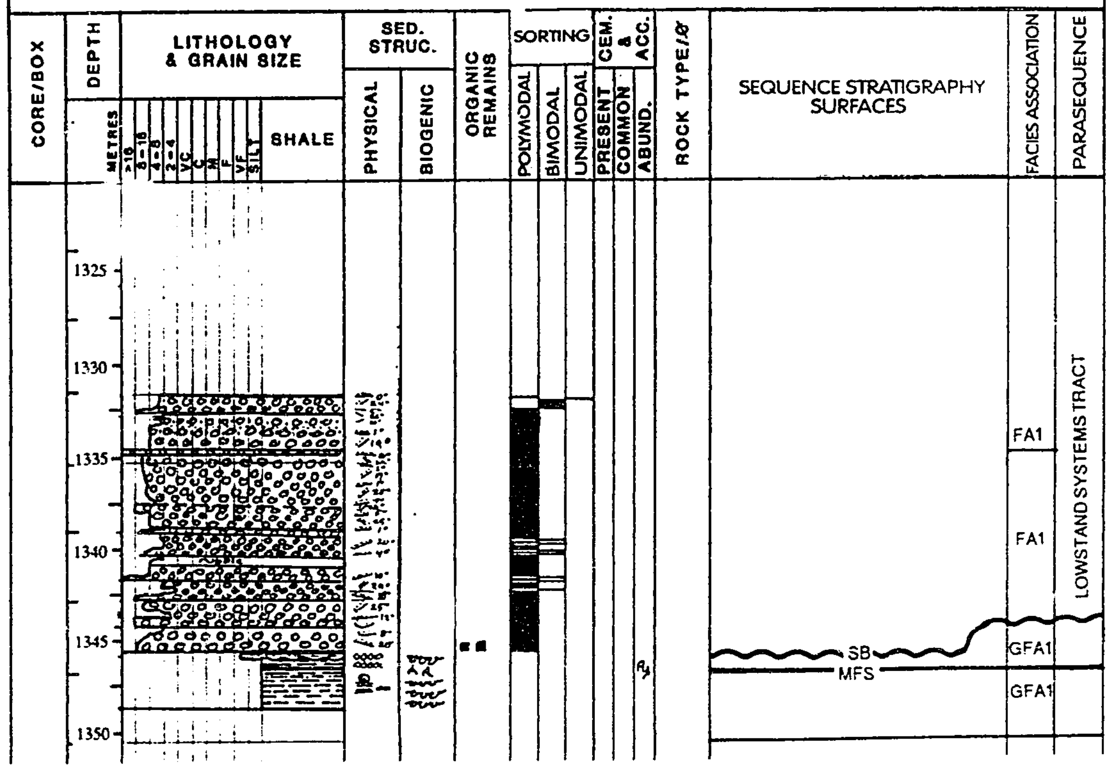
Name - R. Alway
Date - October, 1992

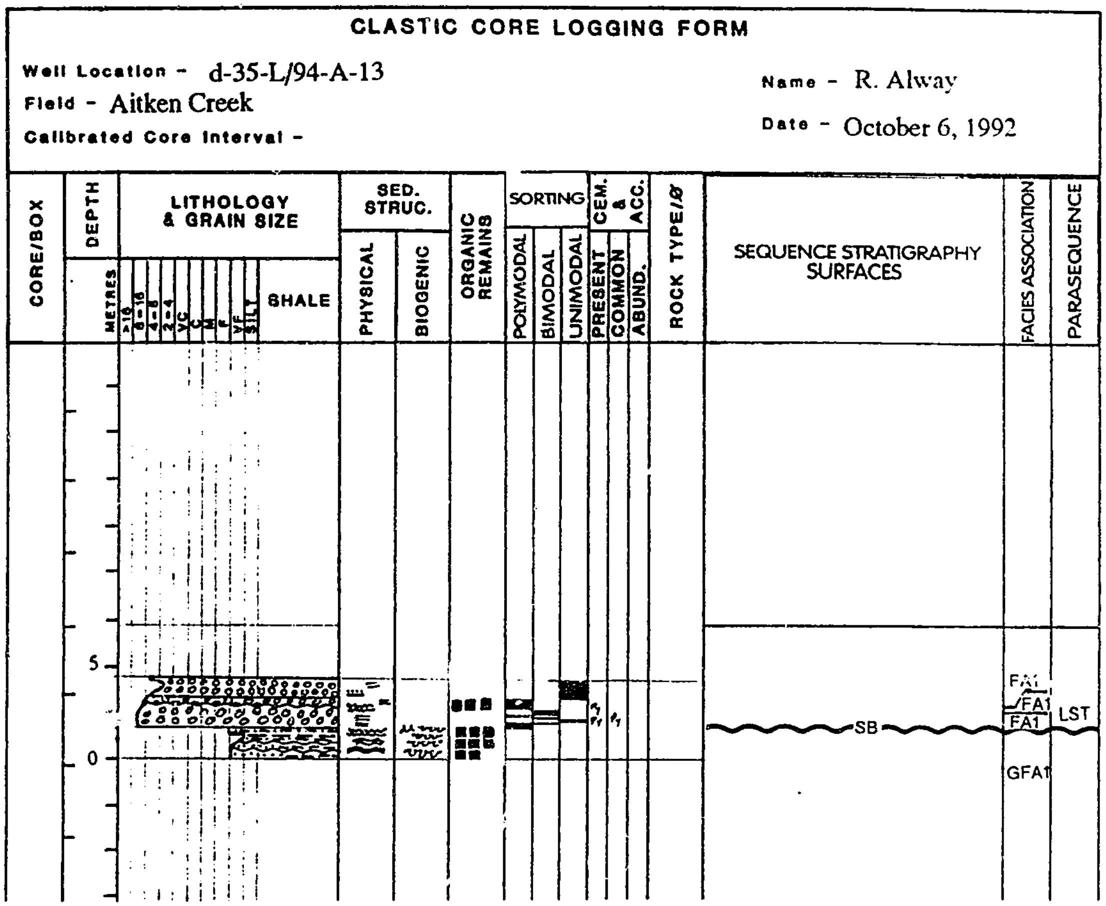


CLASTIC CORE LOGGING FORM

Well Location - d-34-L/94-A-13
Field - Aitken Creek, N.E. B.C.
Calibrated Core Interval - 1325.8 - 1348.7 m

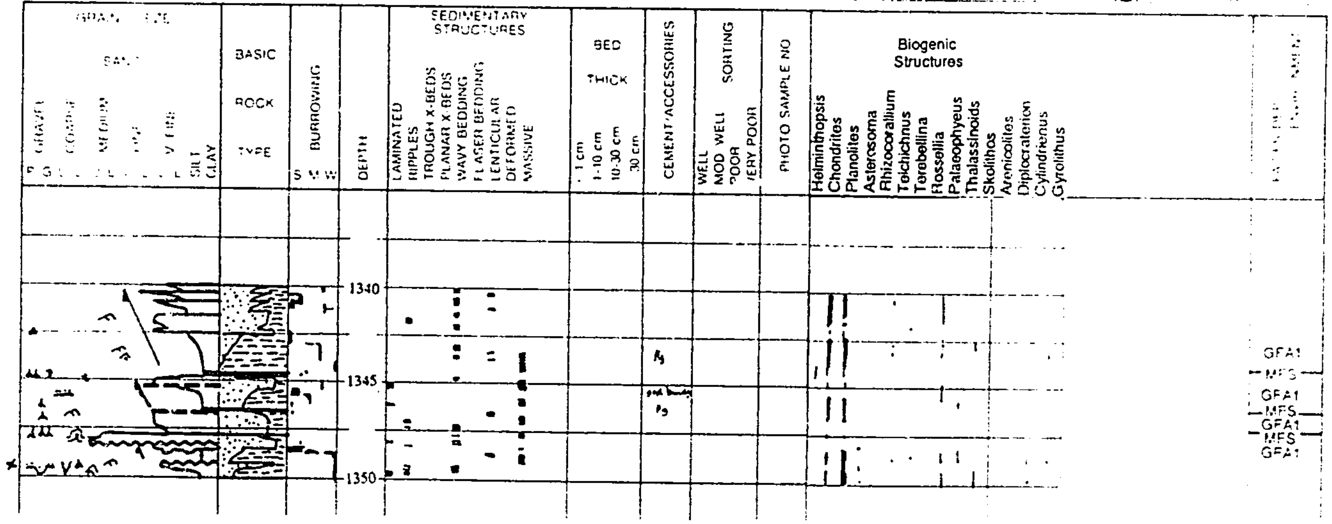
Name - R. Alway
Date - Oct. 6, 1992

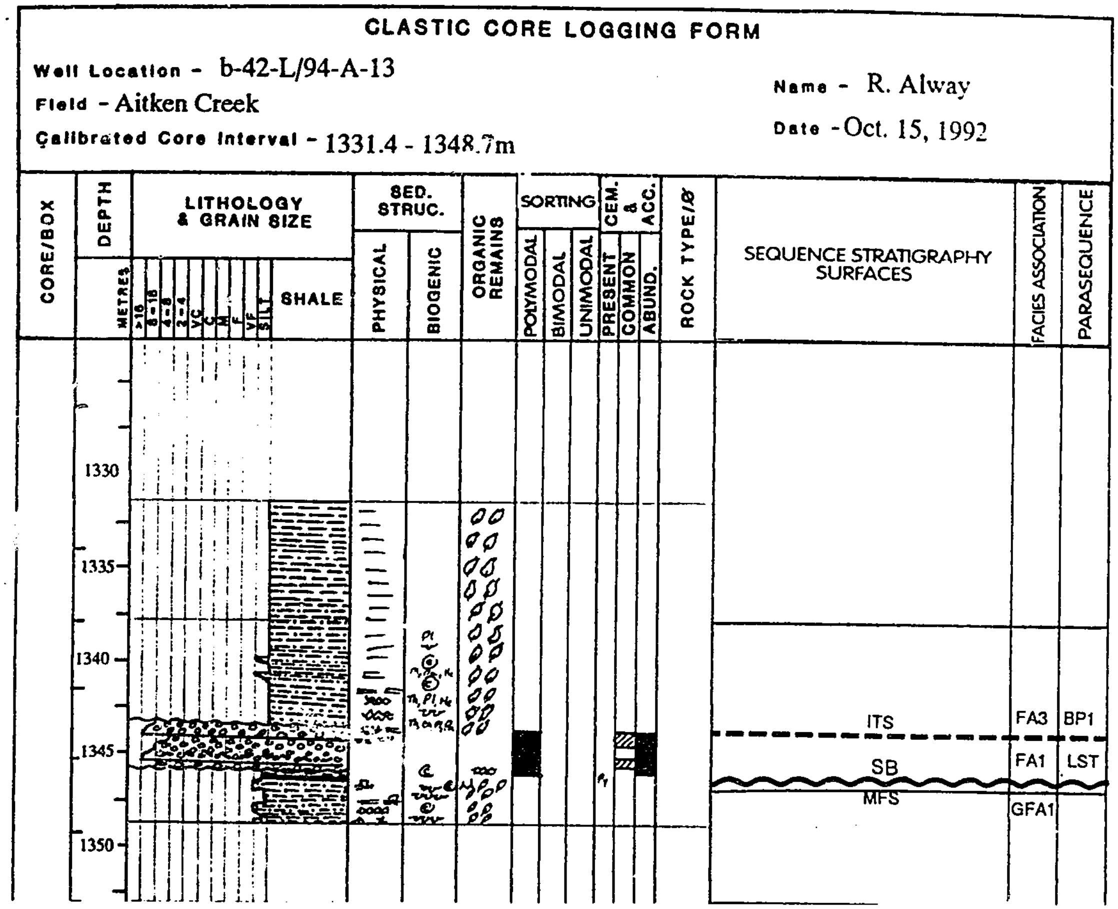


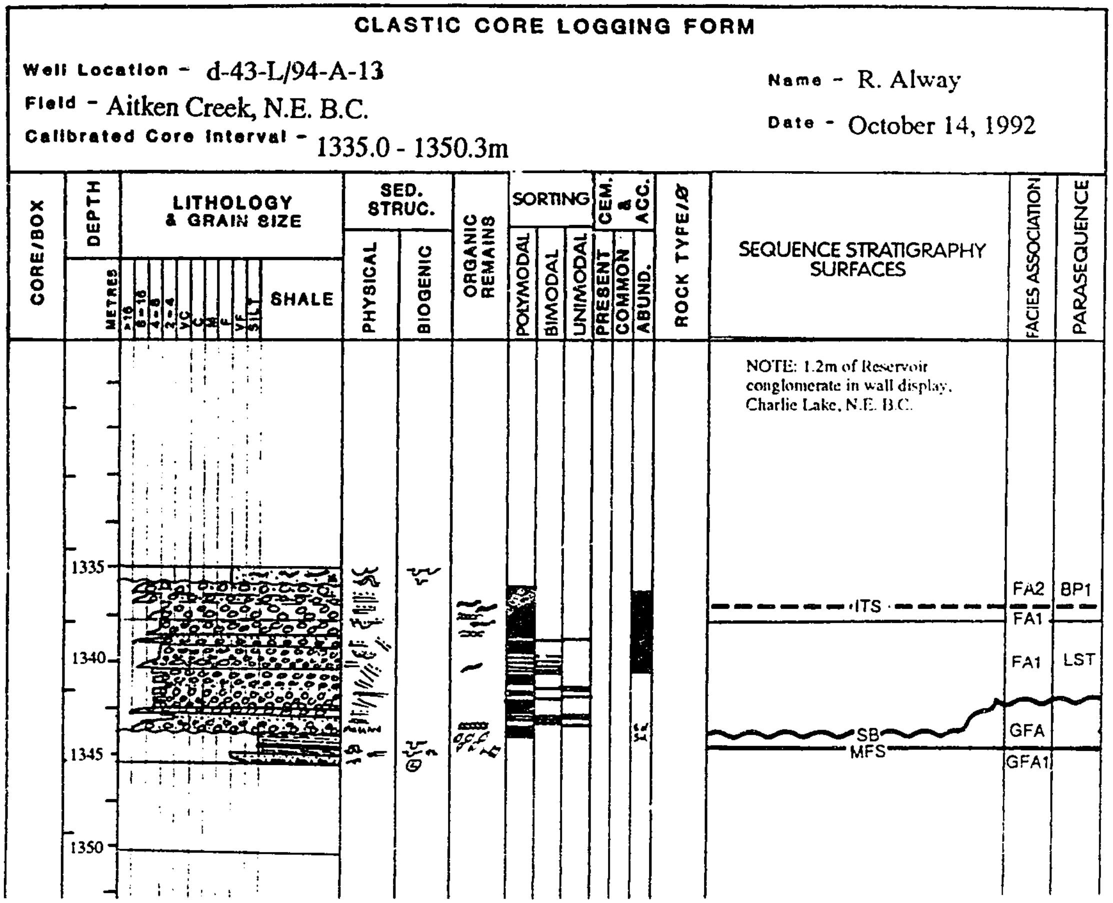

CLASTIC CORE LOGGING FORM
Well Location - d-35-L/94-A-13
Field - Aitken Creek
Calibrated Core Interval -
Name - R. Alway
Date - October 6, 1992
CORE/BOX
DEPTH
METRES
LITHOLOGY & GRAIN SIZE
>16
8-16
4-8
2-4
VC
C
M
F
VF
SILT
SHALE
SED. STRUC.
PHYSICAL
BIOGENIC
ORGANIC REMAINS
SORTING
POLYMODAL
BIMODAL
UNIMODAL
CEM. & ACC.
PRESENT
COMMON
ABUND.
ROCK TYPE/Ø
SEQUENCE STRATIGRAPHY SURFACES
FACIES ASSOCIATION
PARASEQUENCE
5
0
SB
FA1
FA1
FA1
GFA1
LST

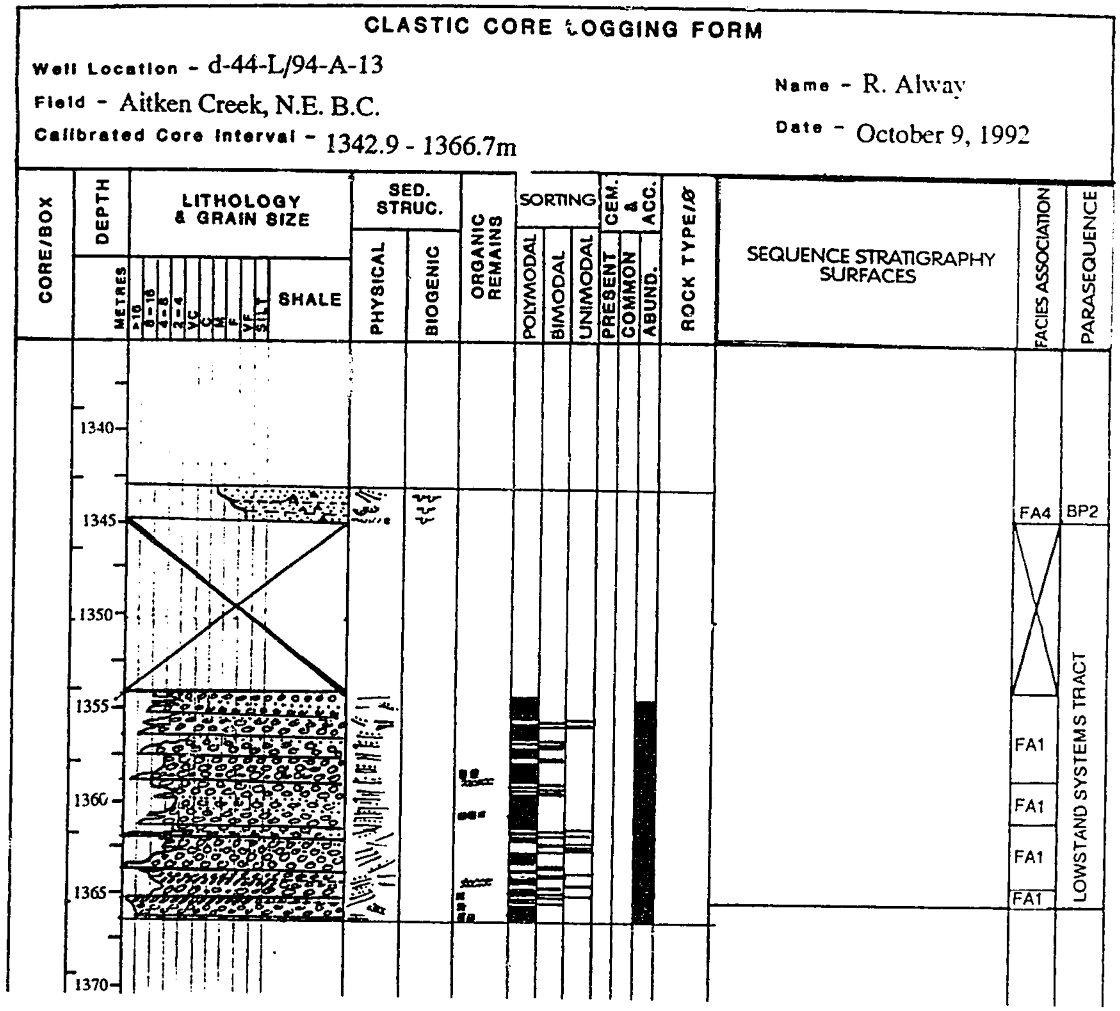
WELL NAME: Union Aitken FORMATION: Gething DATE: Feb. 1994

LOCATION: d-41-L/94-A-13 CORE INTERVAL: 1340.0 - 1350.0m rec 9.9m KB: 950.0m




CLASTIC CORE LOGGING FORM
Well Location - b-42-L/94-A-13
Field - Aitken Creek
Calibrated Core Interval - 1331.4 - 1348.7m
Name - R. Alway
Date - Oct. 15, 1992
CORE/BOX
DEPTH
METRES
LITHOLOGY & GRAIN SIZE
>16
8-16
4-8
2-4
VC
C
M
F
VF
SILT
SHALE
SED. STRUC.
PHYSICAL
BIOGENIC
ORGANIC REMAINS
SORTING
POLYMODAL
BIMODAL
UNIMODAL
CEM. & ACC.
PRESENT
COMMON
ABUND.
ROCK TYPE/Ø
SEQUENCE STRATIGRAPHY SURFACES
FACIES ASSOCIATION
PARASEQUENCE
1330
1335
1340
1345
1350
ITS
SB
MFS
FA3
FA1
GFA1
BP1
LST


CLASTIC CORE LOGGING FORM
Well Location - d-43-L/94-A-13
Field - Aitken Creek, N.E. B.C.
Calibrated Core Interval - 1335.0 - 1350.3m
Name - R. Alway
Date - October 14, 1992
CORE/BOX
DEPTH
METRES
LITHOLOGY & GRAIN SIZE
>16
8-16
4-8
2-4
VC
C
M
F
VF
SILT
SHALE
SED. STRUC.
PHYSICAL
BIOGENIC
ORGANIC REMAINS
SORTING
POLYMODAL
BIMODAL
UNIMODAL
CEM. & ACC.
PRESENT
COMMON
ABUND.
ROCK TYPE/Ø
SEQUENCE STRATIGRAPHY SURFACES
FACIES ASSOCIATION
PARASEQUENCE
NOTE: 1.2m of Reservoir conglomerate in wall display, Charlie Lake, N.E. B.C.
1335
1340
1345
1350
ITS
SB
MFS
FA2
FA1
FA1
GFA
GFA1
BP1
LST


CLASTIC CORE LOGGING FORM
Well Location - d-44-L/94-A-13
Field - Aitken Creek, N.E. B.C.
Calibrated Core Interval - 1342.9 - 1366.7m
Name - R. Alway
Date - October 9, 1992
CORE/BOX
DEPTH
METRES
LITHOLOGY & GRAIN SIZE
SHALE
SED. STRUC.
PHYSICAL
BIOGENIC
ORGANIC REMAINS
SORTING
POLYMODAL
BIMODAL
UNIMODAL
CEM. & ACC.
PRESENT
COMMON
ABUND.
ROCK TYPE/Ø
SEQUENCE STRATIGRAPHY SURFACES
FACIES ASSOCIATION
PARASEQUENCE
1340
1345
1350
1355
1360
1365
1370
FA4
BP2
FA1
FA1
FA1
FA1
LOWSTAND SYSTEMS TRACT

CLASTIC CORE LOGGING FORM

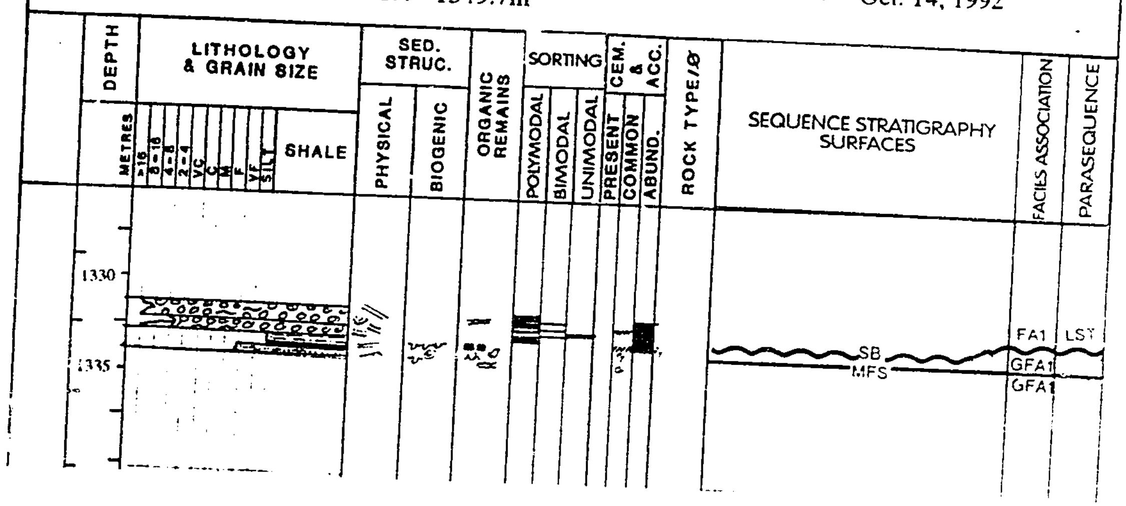
Well Location - d-45-L/94-A-13

Field - Aitken Creek, N.E. B.C.

Calibrated Core Interval - 1331.4 - 1349.7m

Name - R. Alway

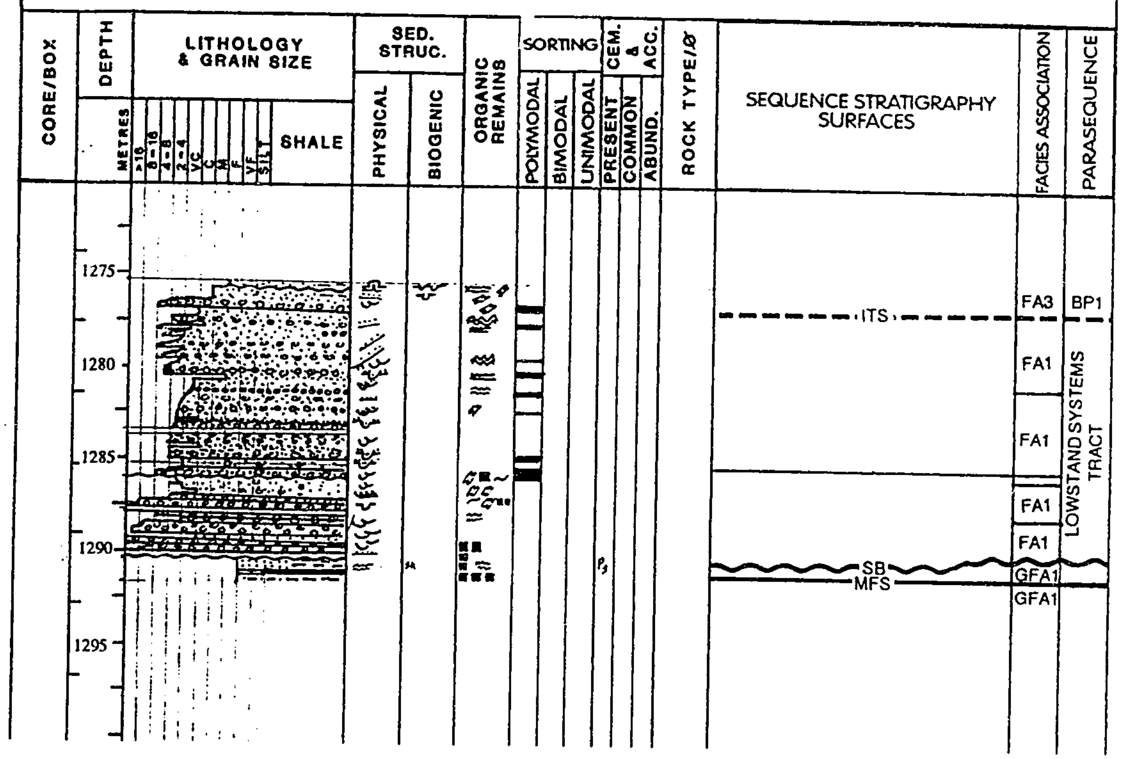
Date - Oct. 14, 1992



CLASTIC CORE LOGGING FORM

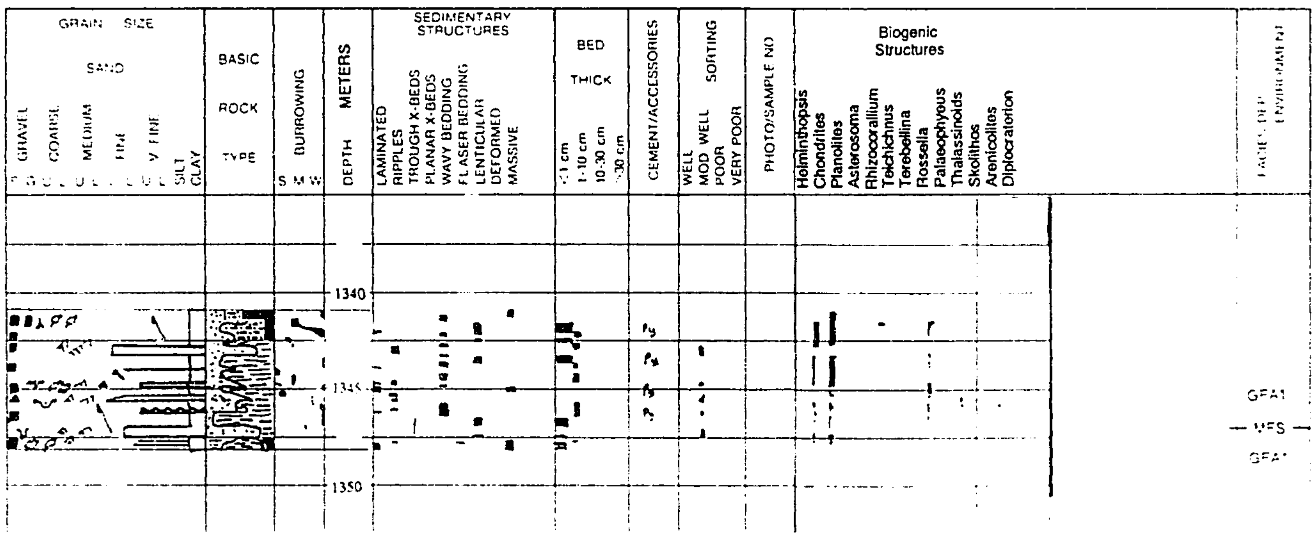
Well Location - d-47-L/94-A-13
Field - Aitken Creek
Calibrated Core Interval - 1275.4 - 1291.7 m

Name - R. Alway
Date - October, 1992



WELL NAME: Union Aitken   FORMATION: Gething   DATE: Feb. 1994

LOCATION: a-53-L/94-A-13   CORE INTERVAL: 1314.4 - 1348.4m   KB:



CLASTIC CORE LOGGING FORM

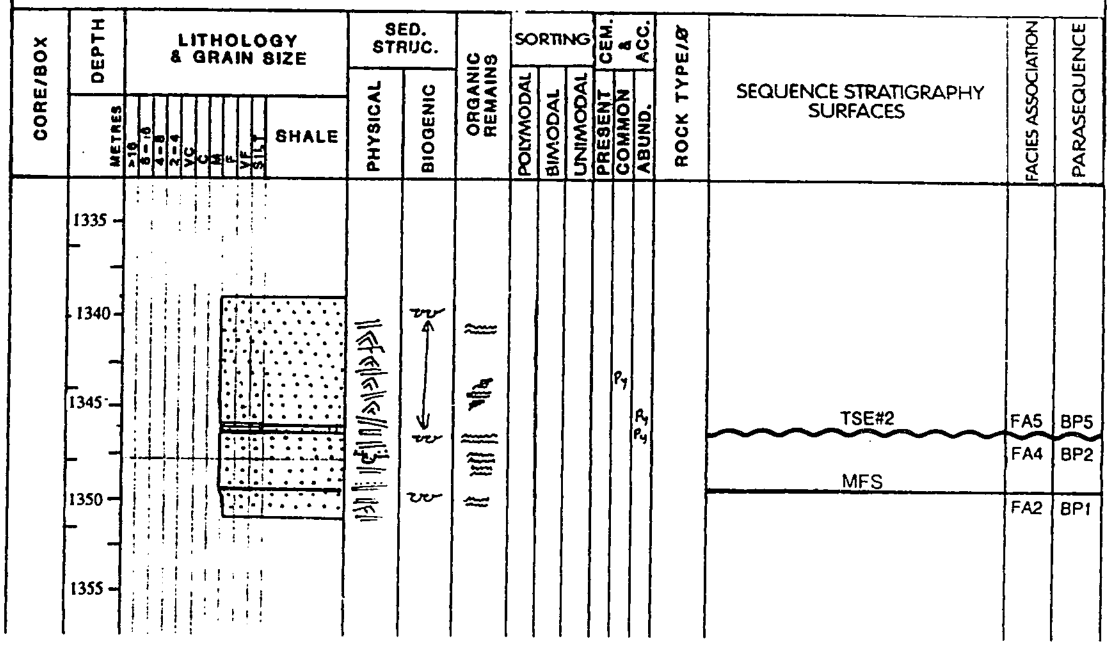
Well Location - b-54-L/94-A-13

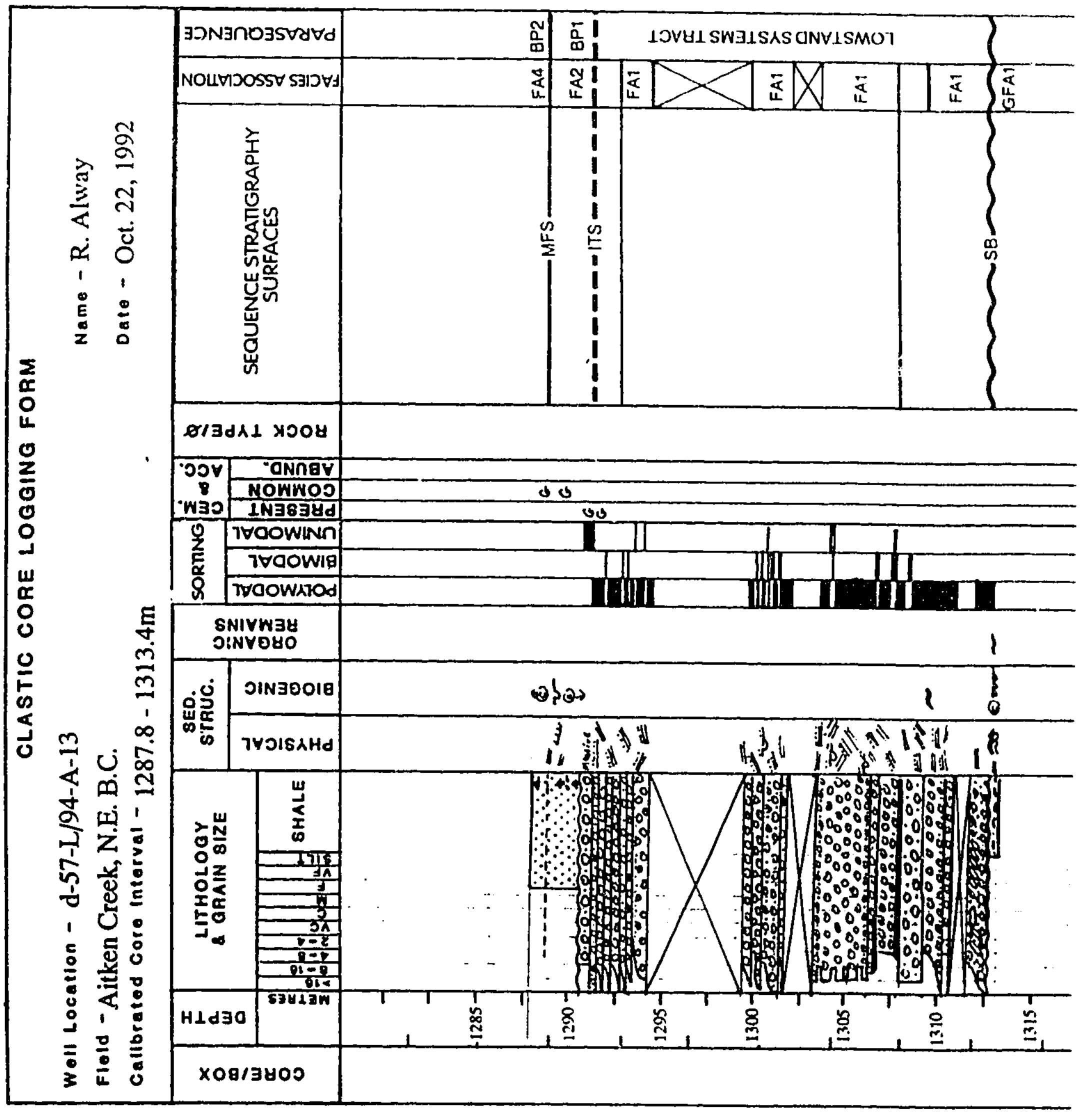
Field - Aitken Creek, N.E. B.C.

Calibrated Core Interval - 1339.9 - 1351.0 m

Name - R. Alway

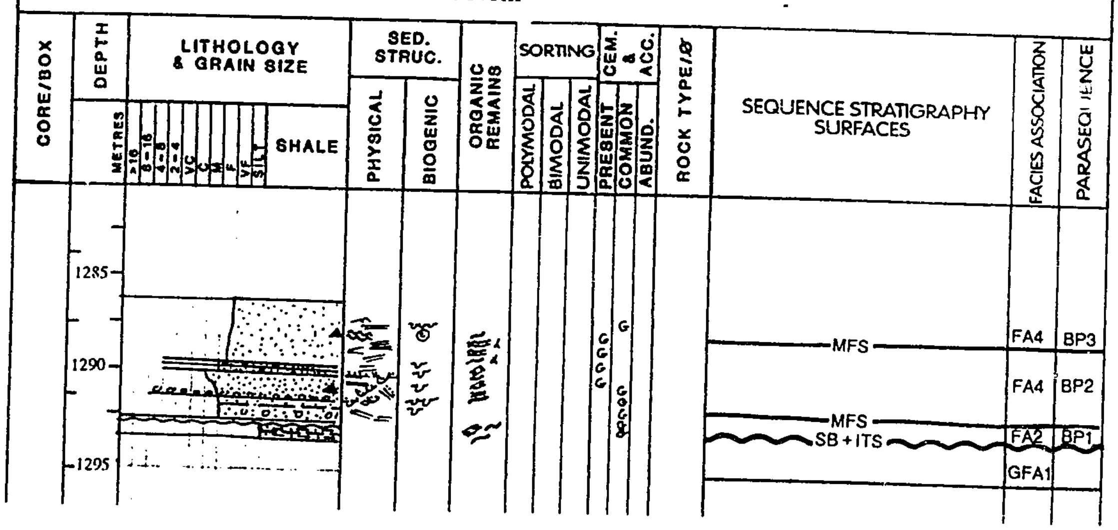
Date - Oct. 16, 1992




CLASTIC CORE LOGGING FORM
Well Location - d-57-L/94-A-13
Field - Aitken Creek, N.E. B.C.
Calibrated Core Interval - 1287.8 - 1313.4m
Name - R. Alway
Date - Oct. 22, 1992
CORE/BOX
DEPTH
METRES
LITHOLOGY & GRAIN SIZE
SHALE
SILT
VF
F
M
C
VC
2-4
4-8
8-16
>16
SED. STRUC.
PHYSICAL
BIOGENIC
ORGANIC REMAINS
SORTING
POLYMODAL
BIMODAL
UNIMODAL
CEM. & ACC.
PRESENT
COMMON
ABUND.
ROCK TYPE/Ø
SEQUENCE STRATIGRAPHY SURFACES
FACIES ASSOCIATION
PARASEQUENCE
1285
1290
1295
1300
1305
1310
1315
MFS
ITS
SB
FA4
FA2
FA1
FA1
FA1
FA1
GFA1
BP2
BP1
LOWSTAND SYSTEMS TRACT

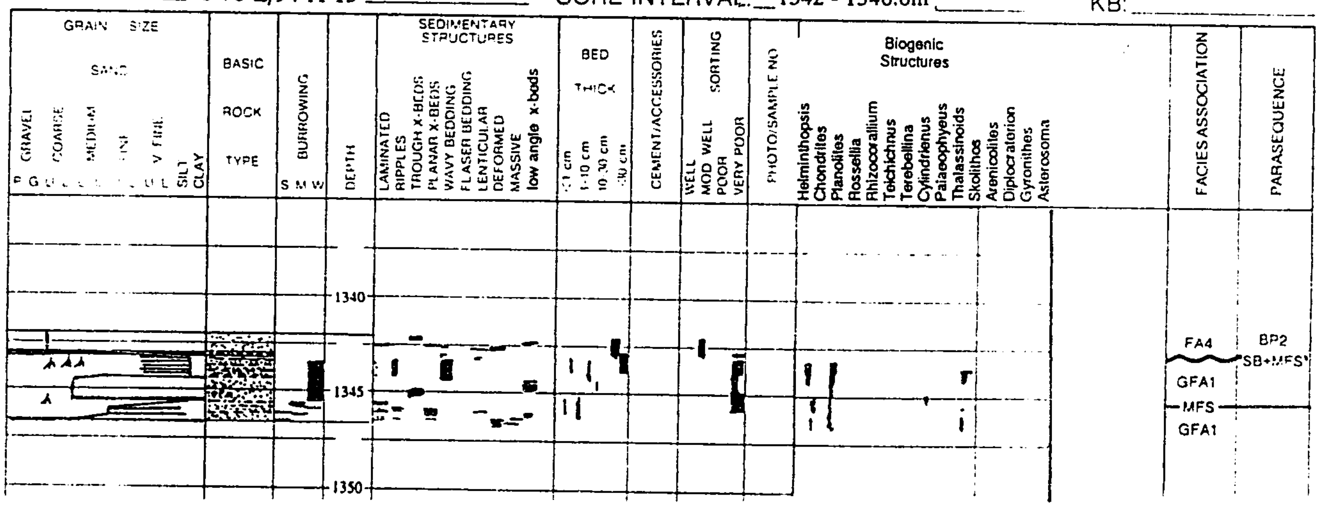
CLASTIC CORE LOGGING FORM

Well Location - d-59-L/94-A-13
Field - Aitken Creek, N.E. B.C.
Calibrated Core Interval - 1286.3 - 1293.6m
Name - R. Alway
Date - Oct. 22, 1992



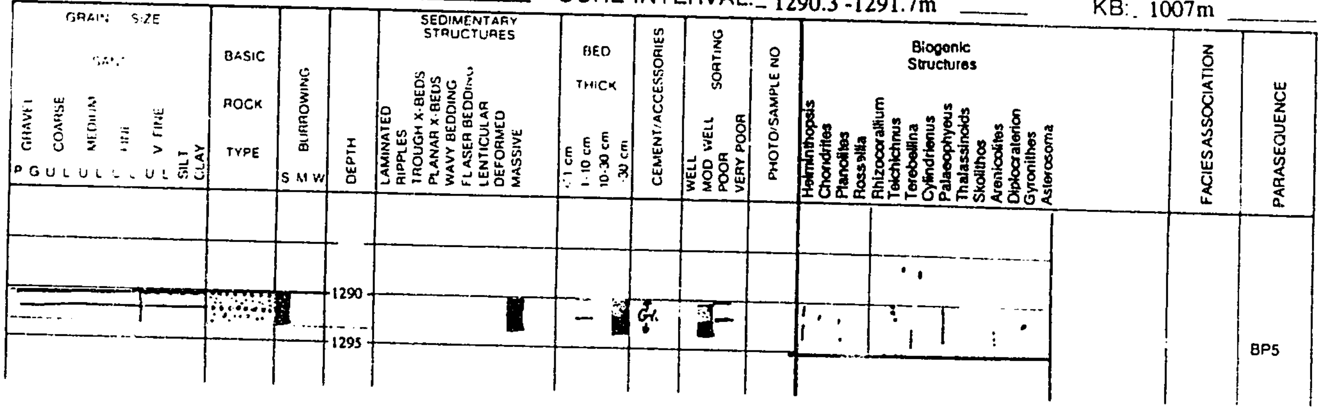
WELL NAME: Union Aitken FORMATION: Bluesky/Gething DATE:

LOCATION: b-70-L/94-A-13 CORE INTERVAL: 1342 - 1346.6m KB:



WELL NAME: Sun *et al.* FORMATION: Bluesky DATE: Feb. 23, 1992

LOCATION: b-3-I/94-B-16 CORE INTERVAL: 1290.3 -1291.7m KB: 1007m



WELL NAME: Union HB Pine Pass Aitken

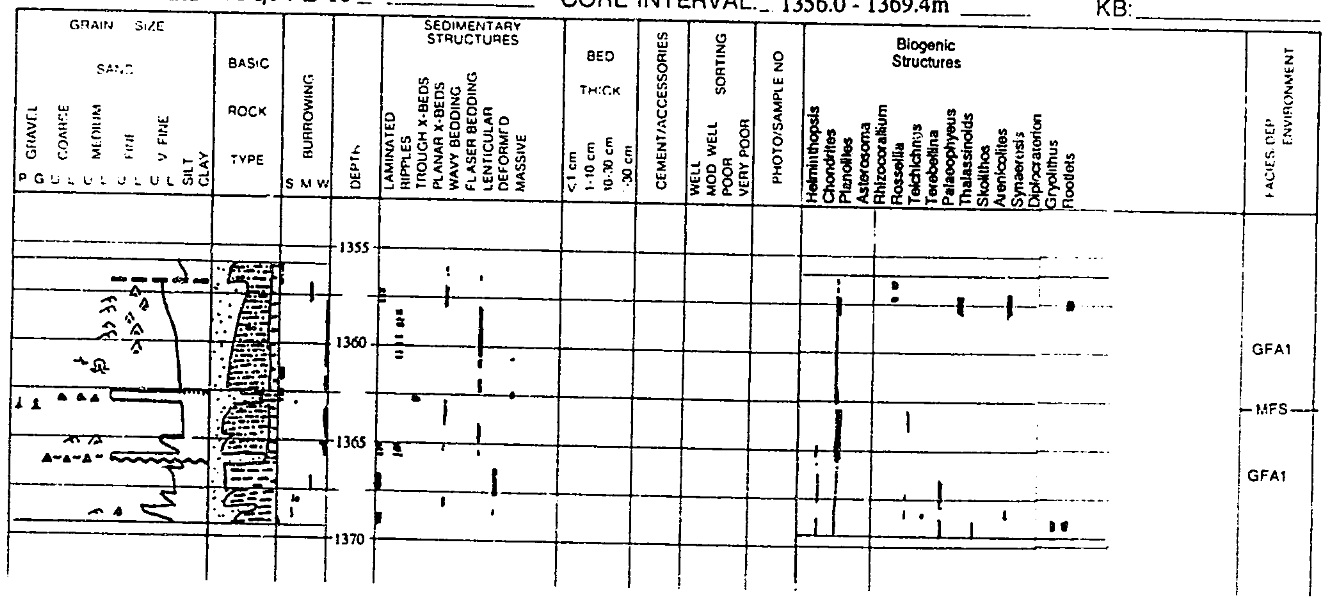
FORMATION: Gething

DATE: Feb. 4, 1994

LOCATION: d-71-I/94-B-16

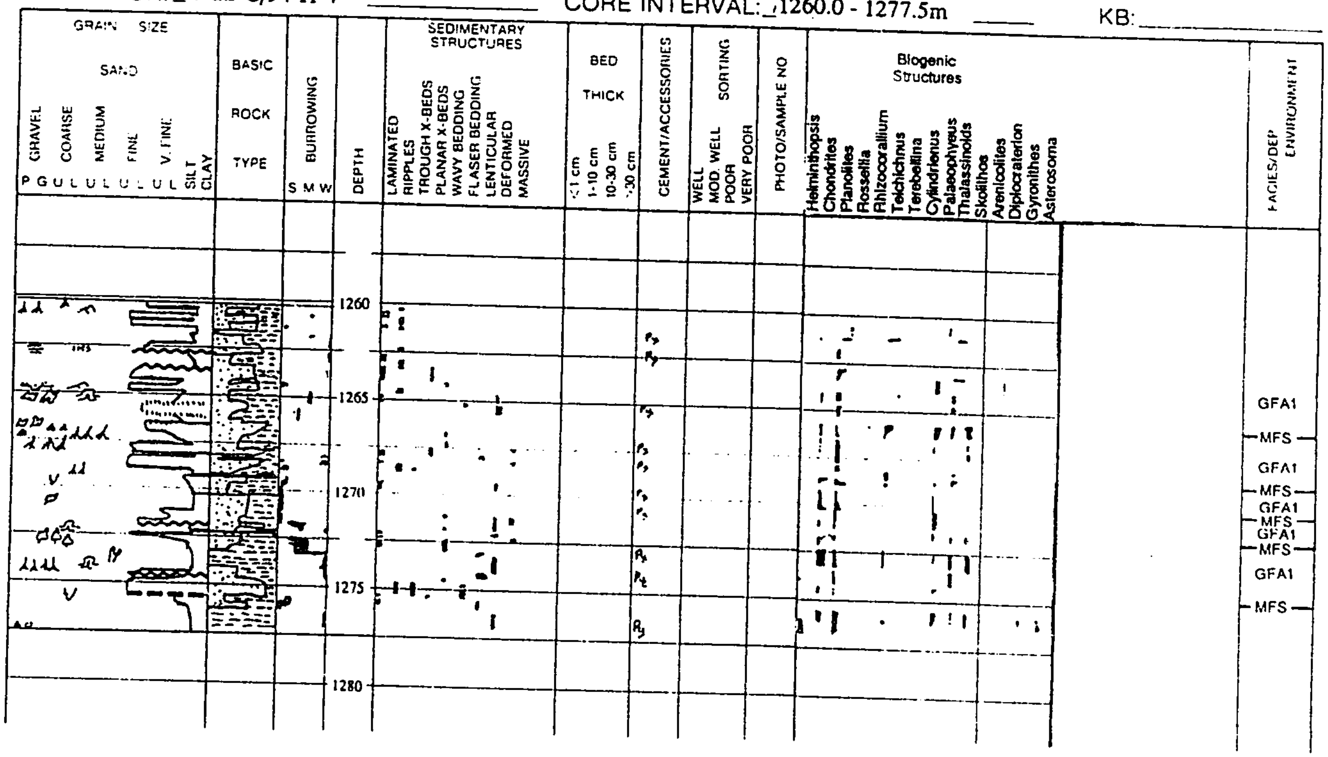
CORE INTERVAL: 1356.0 - 1369.4m

KB:



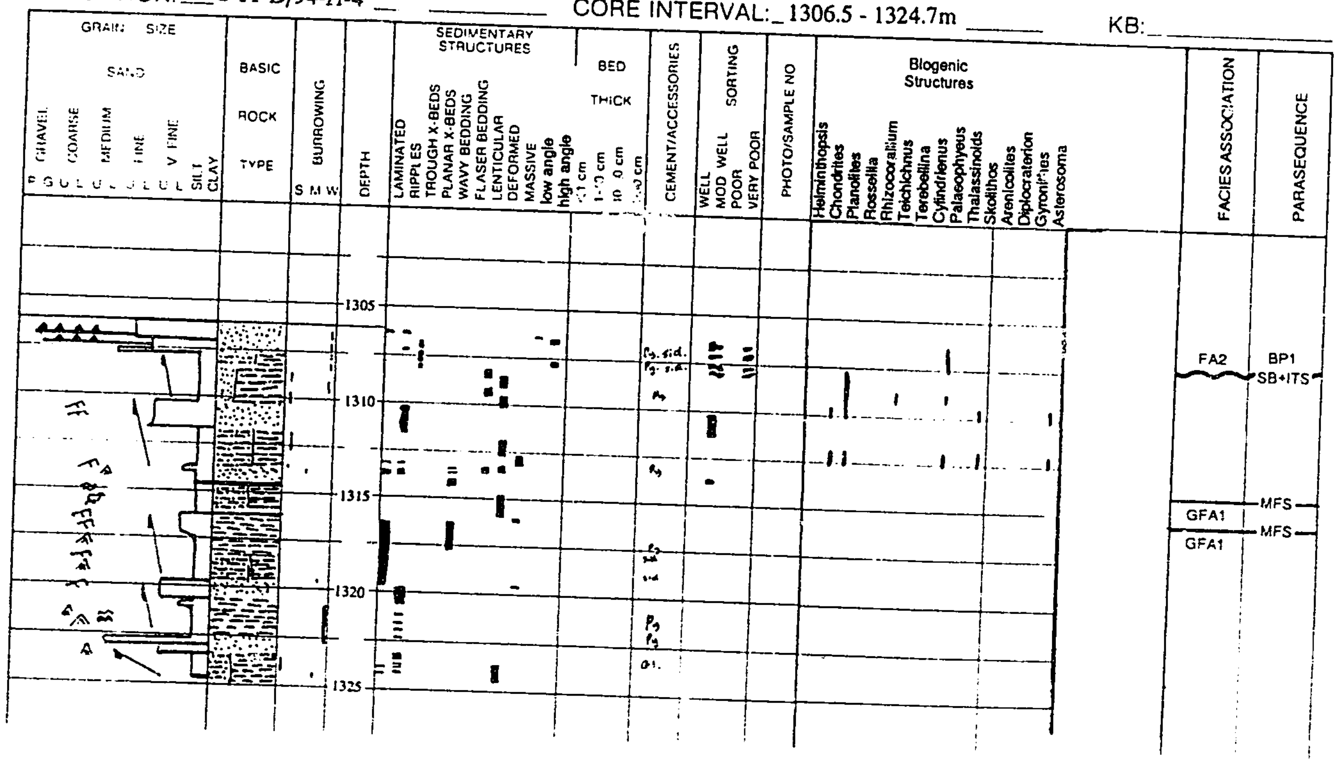
WELL NAME: Czar *et al.* NIG FORMATION: Gething DATE: Feb. 1992

LOCATION: b-22-C/94-H-4 CORE INTERVAL: 1260.0 - 1277.5m KB:



WELL NAME: Dome W. NIG FORMATION: Gething DATE: March 3, 1993

LOCATION: d-11-D/94-H-4 CORE INTERVAL: 1306.5 - 1324.7m KB:



CLASTIC CORE LOGGING FORM

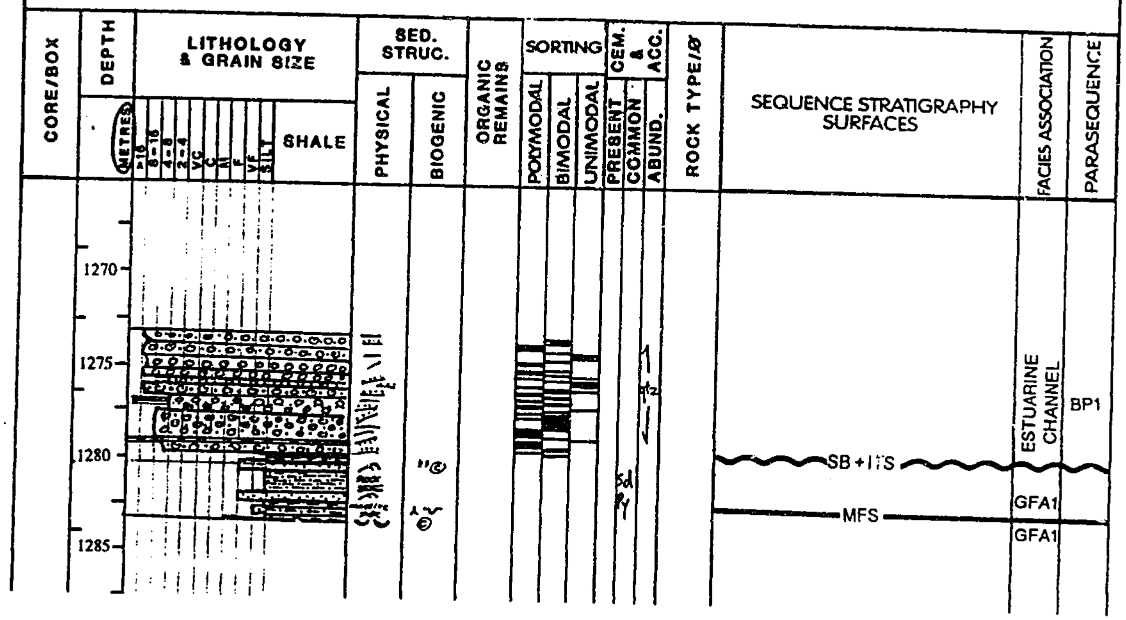
Well Location - b-41-A/94-G-1

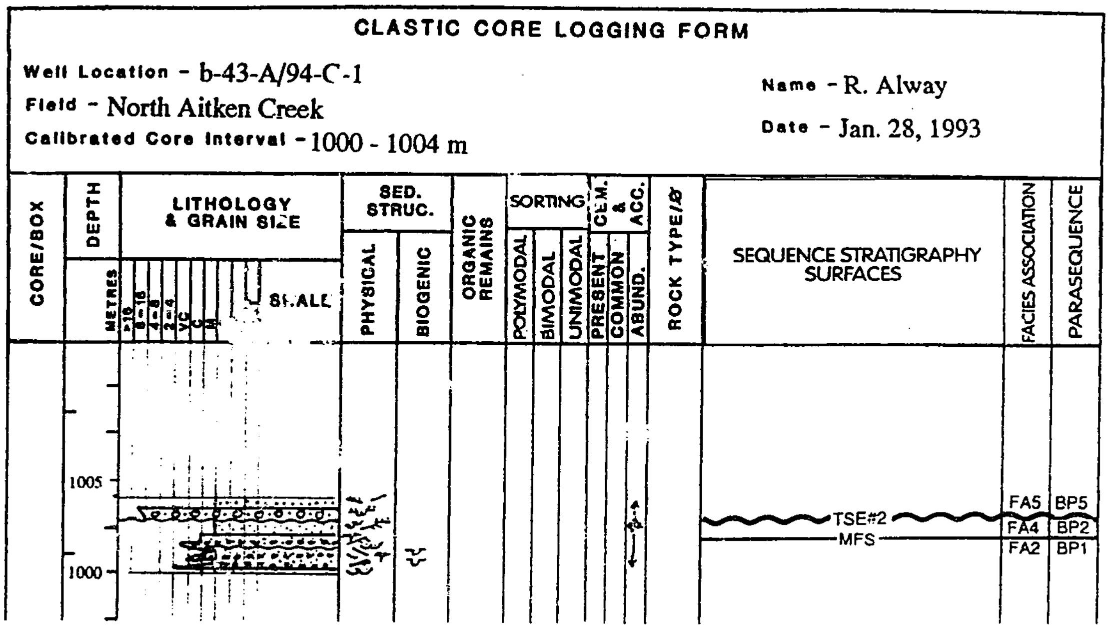
Field - North Aitken Creek

Calibrated Core Interval - 1271 - 1284 m

Name - R. Alway

Date - January 28, 1993




CLASTIC CORE LOGGING FORM
Well Location - b-43-A/94-C-1
Field - North Aitken Creek
Calibrated Core Interval - 1000 - 1004 m
Name - R. Alway
Date - Jan. 28, 1993
CORE/BOX
DEPTH
METRES
LITHOLOGY & GRAIN SIZE
SHALE
SED. STRUC.
PHYSICAL
BIOGENIC
ORGANIC REMAINS
SORTING
POLYMODAL
BIMODAL
UNIMODAL
CEM. & ACC.
PRESENT
COMMON
ABUND.
ROCK TYPE
SEQUENCE STRATIGRAPHY SURFACES
FACIES ASSOCIATION
PARASEQUENCE
1005
1000
TSE#2
MFS
FA5
FA4
FA2
BP5
BP2
BP1

APPENDIX B - BLUESKY TRANSGRESSIVE SYSTEMS TRACT PARASEQUENCE ISOPACH THICKNESS DATA.

WELL LOCATION	Basal Bluesky (m	BP1	BP2	BP3	BP4	BP5
c-40-E/94-A-13	-308	0.00	0.00	0.00	0.00	2.40
a-50-E/94-A-13	-313	0.00	0.00	0.00	0.00	0.00
a-83-E/94-A-13	-385.9	0.00	0.00	0.00	0.00	1.50
b-02-F/94-A-13	-376.4	9.50	8.50	2.40	0.00	2.40
b-10-F/94-A-13	-376.4	0.00	0.00	0.00	0.00	3.10
d-11-F/94-A-13	-378.4	10.00	6.20	1.20	0.00	2.20
b-24-F/94-A-13	-375.8	10.00	5.00	2.90	0.00	1.40
c-28-F/94-A-13		11.00	6.40	?	0.00	?
b-32-F/94-A-13	-358	0.00	0.00	0.00	0.00	0.00
c-54-F/94-A-13	-374.1	0.00	0.00	0.00	0.00	1.00
d-79-F/94-A-13	-384.2	0.00	0.00	0.00	0.00	1.80
a-81-F/94-A-13	-386	0.00	0.00	0.00	0.00	3.00
d-97-F/94-A-13	-385.2	9.70	3.80	2.10	0.00	3.70
a-05-K/94-A-13	-404	8.00	2.10	3.00	0.00	2.00
c-11-K/94-A-13	-386.1	10.40	3.70	2.70	0.00	1.50
[illegible]19-K/94-A-13	-387.4	8.20	3.10	2.10	0.00	0.90
d-51-K/94-A-13	-369.9	[illegible]	3.80	0.00	0.00	3.10
d-59-K/94-A-13	-368	[illegible]	2.40	0.00	0.00	2.00
d-64-K/94-A-13	-359.6	[illegible]	4.80	0.00	4.80	1.8[illegible]
d-73-K/94-A-13	-380.1	[illegible]	2.20	3.00	5.70	2.20
b-88-K/94-A-13	-372.3	11.[illegible]	0.00	0.00	3.80	1.10
d-03-L/94-A-13	-394.7	12.50	2.00	0.00	0.00	1.90
d-04-L/94-A-13	-398.5	12.20	2.00	0.00	0.00	2.00
a-05-L/94-A-13	-389.8	8.53	1.80	0.00	0.00	1.80
d-21-L/94-A-13	-390.2	0.00	0.00	0.00	0.00	2.00
d-22-L/94-A-13	-359	0.00	0.00	0.00	0.00	2.00
d-23-L/94-A-13	-395.3	0.00	0.00	0.00	0.00	2.40
d-24-L/94-A-13	-390.7	3.70	0.00	0.00	7.90	5.80
d-25-L/94-A-13	-388.3	6.10	0.00	0.00	7.60	1.80
d-26-L/94-A-13	-384	0.00	5.50	0.00	0.00	1.20
d-29-L/94-A-13	-386	4.30	3.70	0.00	0.00	1.80
d-30-L/94-A-13	-369.1	0.00	0.00	0.00	0.00	2.40
b-33-L/94-A-13	-400	9.30	0.00	0.00	4.90	3.50
d-33-L/94-A-13	-396	9.80	0.00	0.00	4.30	3.70
d-34-L/94-A-13	-398.1	7.90	0.00	0.00	4.30	3.70
d-35-L/94-A-13	-393.2	9.10	3.10	0.00	0.00	2.40
d-37-L/94-A-13	-381	0.00	3.10	0.00	0.00	1.80
d-41-L/94-A-13	-382.8	0.00	0.00	0.00	1.00	4.00
b-42-L/94-A-13	-389.5	9.20	0.00	0.00	4.80	3.10
b-43-L/94-A-13	-393.4	9.10	0.00	0.00	1.80	3.70
d-43-L/94-A-13		0.00	1.80	0.00	0.00	4.30
d-44-L/94-A-13	-392.6	6.10	1.80	0.00	0.00	5.50
b-45-L/94-A-13		0.00	0.00	0.00	0.00	0.00
d-45-L/94-A-13	-385	4.90	4.30	0.00	0.00	3.10
a-46-L/94-A-13	-391.4	6.20	1.20	0.00	0.00	4.00
d-47-L/94-A-13	-383.4	3.70	4.90	0.00	0.00	1.80
d-52-L/94-A-13	-377	0.00	0.00	0.00	5.50	2.40
a-53-L/94-A-13	-385.2	10.40	1.80	0.00	1.50	2.40
b-54-L/94-A-13	-388	5.50	3.60	0.00	0.00	7.00
d-57-L/94-A-13	-384.6	4.30	2.40	0.00	0.00	2.40

d-59-L/94-A-13	-375.5	5.50	3.70	1.50	0.00	1.80
d-64-L/94-A-13	-368.4	0.00	0.00	0.00	0.00	[illegible]
b-70-L/94-A-13	-380.4	3.60	3.70	1.20	0.00	[illegible]
a-63-G/94-B-16	-339.6	0.00	13.30	0.00	0.00	0.00
a-08-H/94-B-16	-314.9	0.00	5.50	2.10	0.00	2.40
d-19-H/94-B-16	-336.8	8.50	4.90	2.40	0.00	2.40
b-62-H/94-B-16	-309.7	11.20	3.50	1.00	0.00	4.00
d-73-H/94-B-16	-300.5	10.10	4.90	0.00	0.00	4.30
b-87-H/94-B-16		0.00	0.00	0.00	0.00	0.00
d-94-H/94-B-16		NO DATA				
b-03-I/94-B-16	-286	0.00	0.00	0.00	0.00	0.00
b-25-I/94-B-16	-301.6	9.10	4.60	2.40	0.00	0.00
d-26-I/94-B-16	-303.5	9.90	4.20	2.10	0.00	1.50
b-36-I/94-B-16	-321	9.10	5.20	1.80	0.00	2.40
a-47-I/94-B-16	-321	10.70	5.80	1.80	0.00	2.40
a-69-I/94-B-16	-313	0.00	0.00	2.40	0.00	2.40
d-71-I/94-B-16	-372.8	0.00	0.00	0.00	0.00	0.00
b-90-I/94-B-16	-312.8	0.00	5.50	1.30	0.00	2.50
b-41-A/94-G-01	-372	10.40	0.80	1.60	0.00	1.40
b-43-A/94-G-01	-381.7	4.20	0.00	1.00	0.00	2.00
a-83-A/94-G-01	-319.4	NO DATA				
b-02-B/94-G-01	-317.3	7.90	0.00	0.00	0.00	0.00
b-06-C/94-H-4	-360.3	10.10	0.00	0.00	3.40	0.60
c-19-C/94-H-4	-342	0.00	0.00	0.00	0.00	2.80
b-22-C/94-H-4	-362.7	0.00	0.00	0.00	4.90	2.30
a-25-C/94-H-4	-356	0.00	0.00	0.00	0.00	1.80
c-32-C/94-H-4	-377	6.10	2.10	0.00	4.90	3.20
c-34-C/94-H-4	-363.8	8.00	2.10	0.00	0.00	2.40
d-39-C/94-H-4	-347.8	0.00	2.80	0.00	4.30	1.80
b-50-C/94-H-4	-352.6	0.00	0.00	0.00	5.20	1.80
a-58-C/94-H-4		NO DATA				
b-84-C/94-H-4	-373.7	6.70	0.00	0.00	3.30	1.80
d-99-C/94-H-4	-361	0.00	0.00	0.00	0.00	2.80
d-01-D/94-H-4	-366	8.20	2.60	0.80	0.00	2.50
d-11-D/94-H-4	-390.4	8.30	1.70	0.70	0.00	2.80
a-39-D/94-H-4	-362.2	11.00	2.00	0.60	0.00	1.20
c-60-D/94-H-4	-354.5	0.00	0.00	0.00	0.00	1.80
d-65-D/94-H-4	-353.7	5.00	2.90	0.00	0.00	1.10
b-66-D/94-H-4	-358.7	5.20	3.10	0.00	0.00	0.90
[illegible]-77-D/94-H-4	-354.1	0.00	0.00	0.00	0.00	3.90
b-82-D/94-H-4	-357.8	4.00	3.10	0.00	0.00	1.80

BLUE. THIN SECT. TABLE

WELL LOCATION	DEPTH	FA 1	FA 2	FA 3	FA 4	FA 5
A-003-L/094-A-13	1312.5M					X
A-005-L/094-A-13	4380'					X
D-044-L/094-A-13	4349'6"	X				
D-044-L/094-A-13	4356'6"	X				
D-044-L/094-A-13	4366'	X				
D-044-L/094-A-13	4377'7"	X				
D-045-L/094-A-13	4372.5'	X				
B-054-L/094-A-13	1342.92M					X
B-054-L/094-A-13	1348.25 M				X	
D-057-L/094-A-13	4255'		X			
D-057-L/094-A-13	4306'4"	X				
D-057-L/094-A-13	4335'	X				
D-059-L/094-A-13	4221.5'				X	
D-059-L/094-A-13	1293M		X			
D-059-L/094-A-13	4240'		X			

APPENDIX C - FACIES ASSOCIATION POROSITY AND PERMEABILITY DATA

well	facies	k-max	k-90	k-vert	porosity
D-3-L/94-A-13	FA2	1.1	0.98	0.71	0.095
A-5-L/94-A-13	FA5	6	5.6	2.8	0.06
D-25-L/94-A-13	FA1	3787.22	3527.22	2020.89	0.132
D-33-L/94-A-13	FA3	1.35	0	0.29	0.032
D-33-L/94-A-13	FA1	1487.24	1206.74	155.86	0.087
D-34-L/94-A-13	FA1	5325.88	4585.67	919.85	0.117
D-35-L/94-A-13	FA1	993	883	125	0.126
D-43-L/94-A-13	FA2	4.67	4.36	1.66	0.058
D-43-L/94-A-13	FA1	2616.7	2395.3	1101.69	0.156
D-44-L/94-A-13	FA4	0.8	0	0.163	0.073
D-44-L/94-A-13	FA1	3449.33	3342.33	1677.85	0.151
D-45-L/94-A-13	FA1	3486.5	3388.17	1040.17	0.15
D-47-L/94-A-13	FA3	15.1	6.33	0.5	0.05
D-47-L/94-A-13	FA1	8.94	6.33	2.92	0.099
D-54-L/94-A-13	FA5	0.08	0	0	0.059
D-54-L/94-A-13	FA4	0.11	0	0	0.074
D-54-L/94-A-13	FA2	0.09	0	0	0.057
D-57-L/94-A-13	FA4	0.74	0.69	0.32	0.054
D-57-L/94-A-13	FA2	3.11	2.18	0.78	0.096
D-57-L/94-A-13	FA1	92.02	74.9	24.41	0.08
D-59-L/94-A-13	FA4	1.39	1.13	0.33	0.068
D-59-L/94-A-13	FA2	0.09	0	0.07	0.03
B-70-L/94-A-13	FA4	0.81	0	0.5	0.11

facies	k-max	k-90	k-vert	porosity
FA1	2360.8	2156.6	785.4	0.122
FA2	1.61	1.5	0.64	0.067
FA3	8.23	3.17	0.395	0.041
FA4	0.77	0.36	0.26	0.076
FA5	3.04	2.8	1.4	0.06